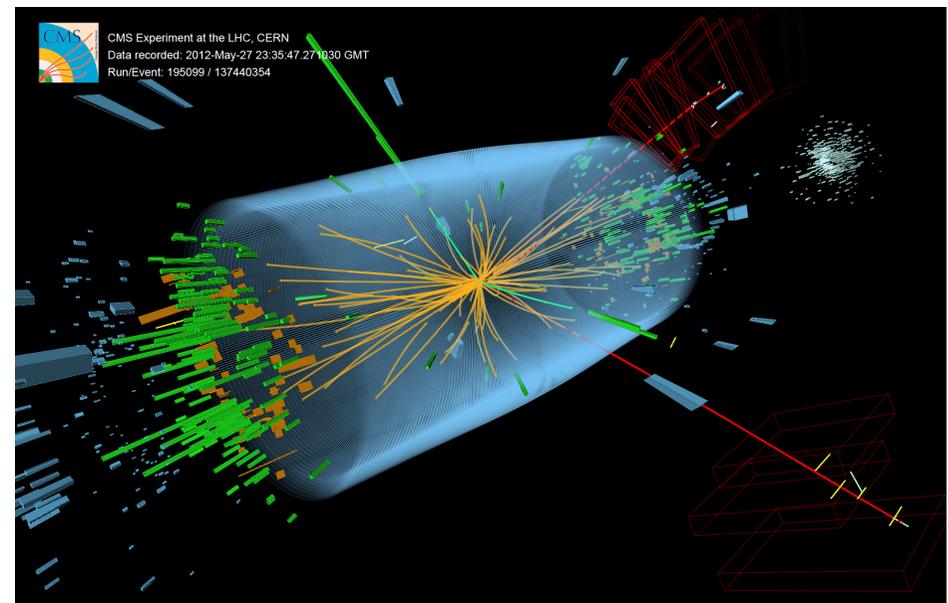
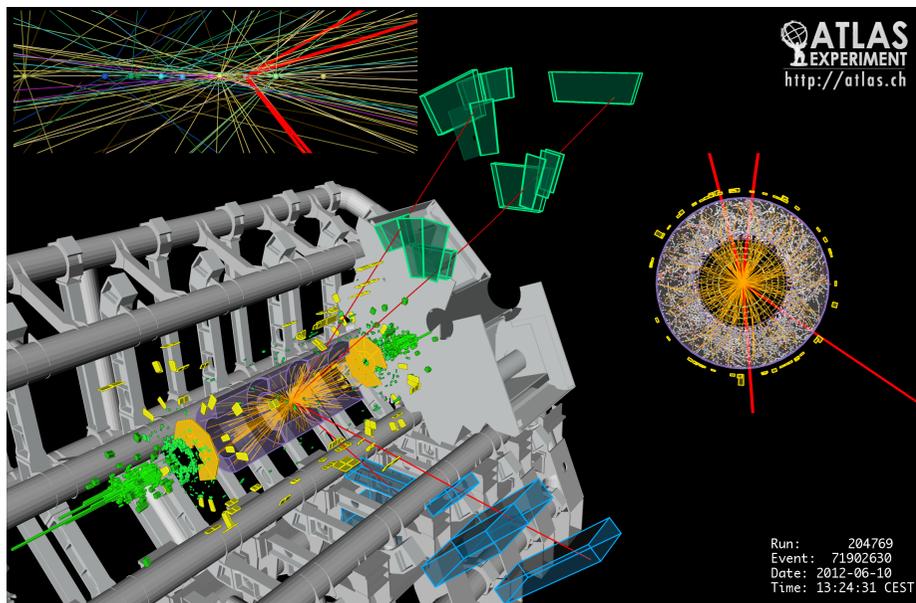


Status of the LHC Spin/mixture studies



Kirill Prokofiev

NYU

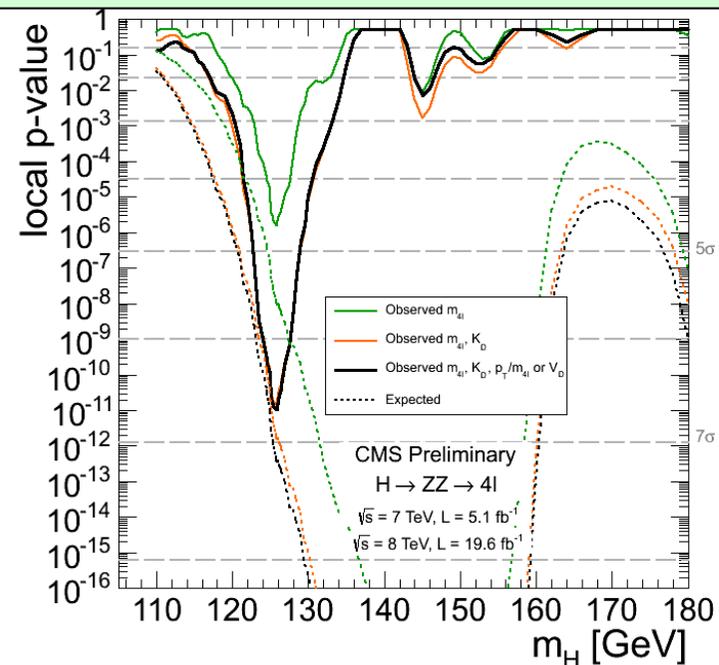
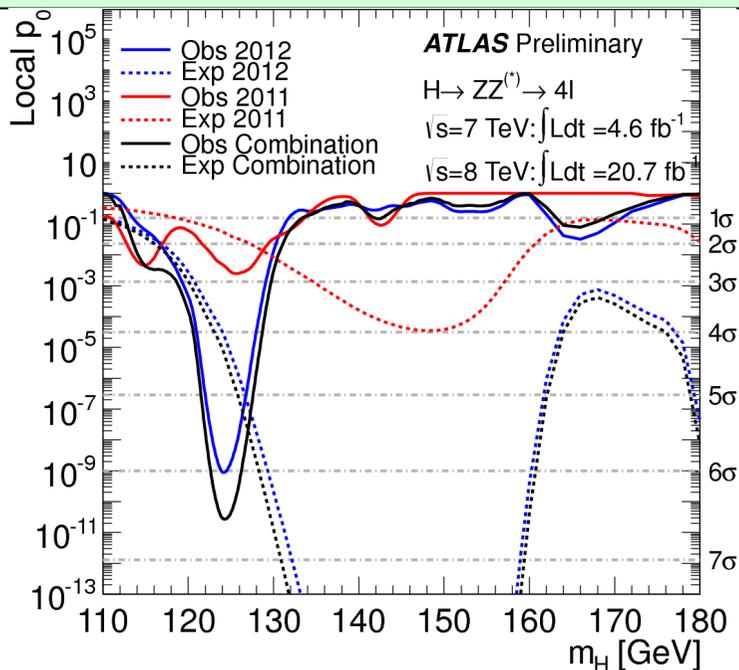


NEW YORK UNIVERSITY



Status of the new boson in ATLAS and CMS

- **ATLAS: Up to 20.7 fb⁻¹ at 8 TeV + 4.6 fb⁻¹ at 7 TeV.**
 - Individual local significances of excess: 7.4 (H→γγ), 6.8 (H→ZZ^(*)→4l) and 3.8 (H→WW→lvlv) standard deviations.
 - $m_H(\gamma\gamma+ZZ) = m_H = 125.5 \pm 0.2 \text{ (stat)}^{+0.5}_{-0.6} \text{ (sys)} \text{ GeV}$.
- **CMS: Up to 19.6 fb⁻¹ at 8 TeV + 5.1 fb⁻¹ at 7 TeV.**
 - Individual local significances of excess: 3.2 (H→γγ), 6.7 (H→ZZ^(*)→4l) and 4.0 (H→WW→lvlv) standard deviations.
 - $m_H(ZZ) = 125.8 \pm 0.5 \text{ (stat)} \pm 0.2 \text{ (sys)} \text{ GeV}$. $m_H(\gamma\gamma) = 125.4 \pm 0.5 \text{ (stat)} \pm 0.6 \text{ (sys)} \text{ GeV}$





Present spin and parity studies in ATLAS and CMS

- In 2012-2013 ATLAS has presented three major studies of the spin and parity of the Higgs-like resonance.
 - Council week: $H \rightarrow ZZ \rightarrow 4l$ and $H \rightarrow \gamma\gamma$.
 - Moriond: $H \rightarrow ZZ \rightarrow 4l$ (update), $H \rightarrow \gamma\gamma$ (update) and $H \rightarrow WW \rightarrow l\nu l\nu$

ATL-CONF-2013-013

ATL-CONF-2013-029

ATL-CONF-2013-031

- CMS has shown two major results:
 - HCP: $H \rightarrow ZZ \rightarrow 4l$.
 - Moriond: $H \rightarrow ZZ \rightarrow 4l$ (update) and $H \rightarrow WW \rightarrow l\nu l\nu$.

CMS-CMS-PAS-HIG-13-002

CMS-PAS-HIG-13-003

- CMS has also published the HCP result in the $4l$ decay channel.
 - Phys. Rev. Lett. 110 (2013) 081803



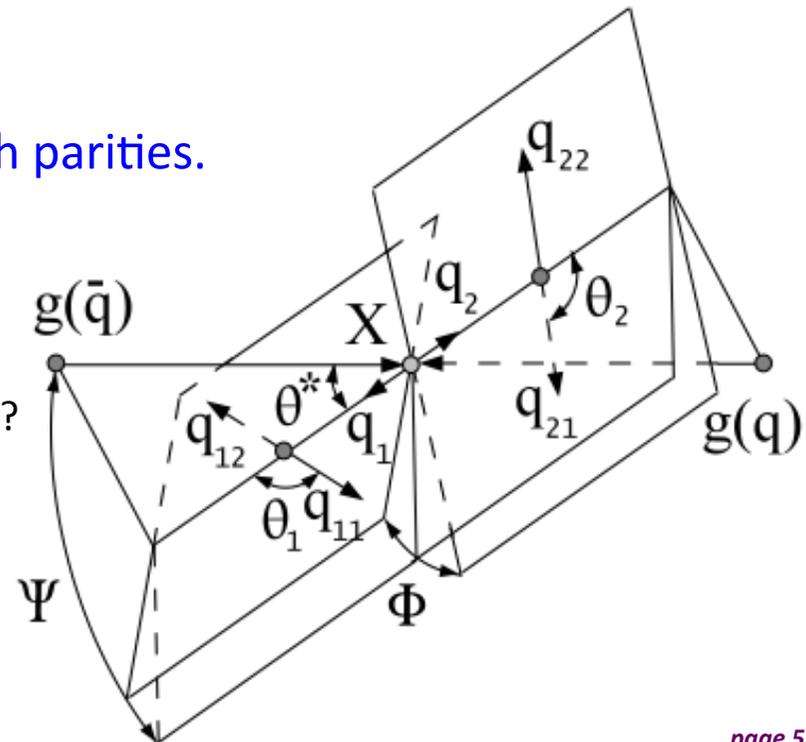
Spin and parity hypotheses

- Both experiments follow in general the formalism described in the JHU papers. In both cases the JHU LO MC generator is used.
 - Y. Gao, *et al.*, *Spin determination of single-produced resonances at hadron colliders*, Phys. Rev. D81 (2010) 075022, arXiv:1001.3396 [hep-ph]
 - S. Bolognesi, *et al.*, *On the spin and parity of a single-produced resonance at the LHC*, Phys. Rev. D86 (2012) 21.
- Exclusion of alternative hypotheses in favor of the Standard Model $J^P=0^+$.
- Models under study:
 - Disentangle if the observed resonance is spin 0, 1 or 2.
 $J^P=0^+$, 1^+ and 2^+_m (Graviton-like tensor with minimal couplings).
 - Both ggF and qq production mechanisms for spin-2 hypotheses.
 - Parity measurement. Exclude spin 0^- hypothesis.
- Further measurements:
 - $J^P = 0^+_h, 1^-, 2^-_h$.



Measurements of Spin and Parity

- Deduce spin and parity from measured distributions of kinematic observables.
 - Angular distributions of decay products in the rest frame of the resonance.
 - Invariant masses of the gauge bosons etc..
- $H \rightarrow \gamma\gamma$: spin 0 and (ggF/qq) spin-2 separation. Spin-1 is disfavored by Landau-Yang theorem.
- $H \rightarrow ZZ(*) \rightarrow 4l$, $H \rightarrow WW \rightarrow l\nu l\nu$: spin 0,1,2; both parities.
- See also: K.Melnikov at Higgs Snowmass workshop in Princeton, January 2013:
<http://physics.princeton.edu/indico/sessionDisplay.py?sessionId=1&slotId=0&confId=127#2013-01-14>





Spin measurements in $H \rightarrow \gamma\gamma$ decay (ATLAS)

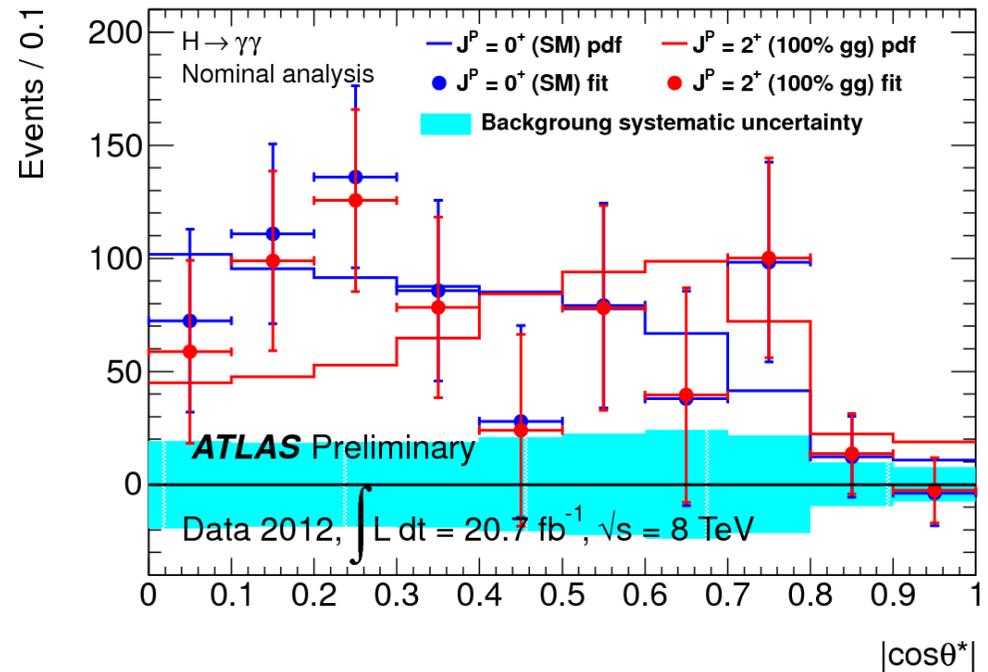
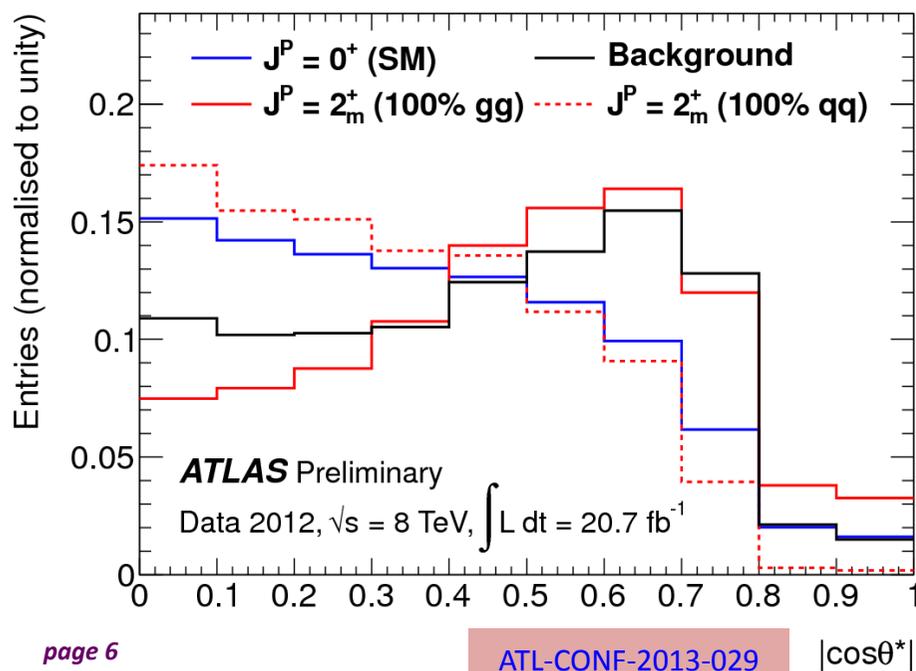
Study based on the single production angle: $|\cos \theta^*|$.

20.7 fb^{-1} at 8 TeV

Considered models: 0^+ and 2_m^+ (both $q\bar{q}$ and gg F production mechanisms).

Signal region: $122 \text{ GeV} < m_{\gamma\gamma} < 130 \text{ GeV}$.

$|\cos \theta^*|$ and $m_{\gamma\gamma}$ are treated as uncorrelated. Fit to the product of their PDFs in the signal region.





Spin measurements in $H \rightarrow \gamma\gamma$ decay (ATLAS)

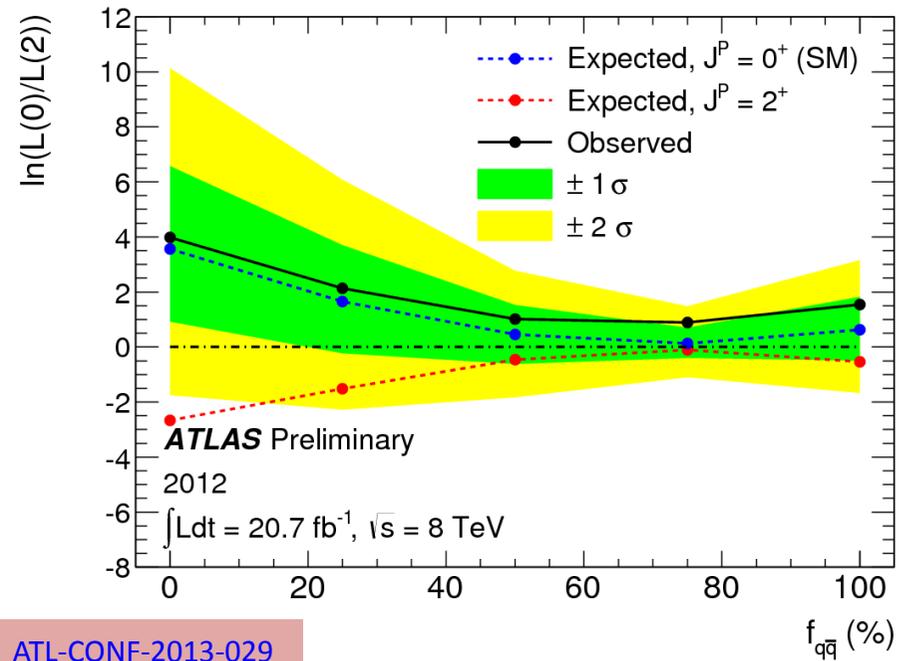
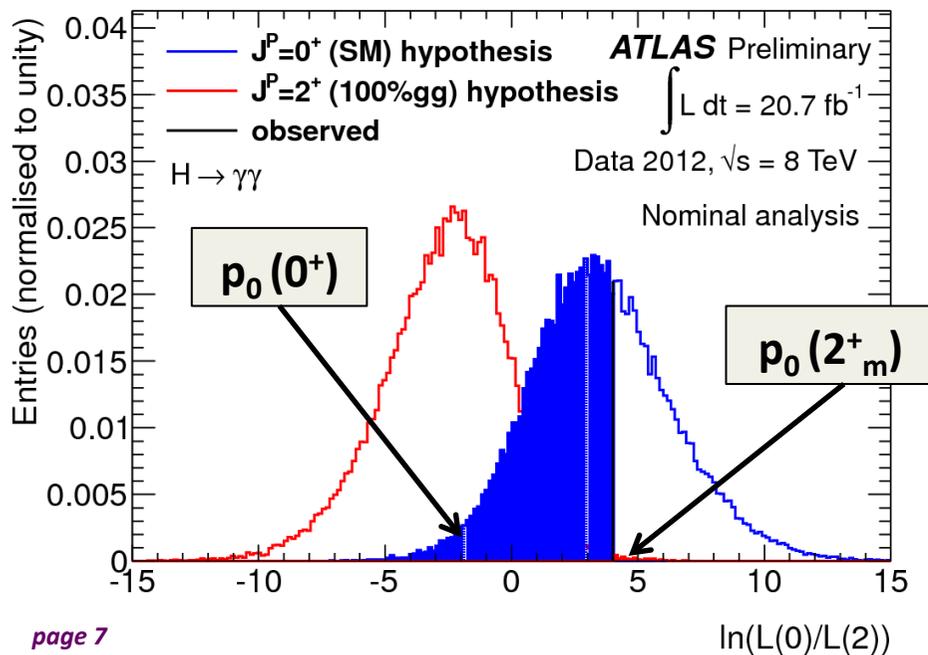
Expected p-value for 2^+_m (100% ggF): 0.5%.

Observed p-value for 2^+_m (100% ggF): 0.3%.

Observed p-value for 0^+ : 58.8%.

Data exclude $J^P=2^+_m$ in favor of $J^P=0^+$ at 99.3% CL.

$f_{q\bar{q}}$ (%)	Spin hypothesis	p-values (%)		$1 - \text{CL}_S(2^+) (%)$
		expected	observed	
0	0^+	1.2	58.8	99.3
	2^+	0.5	0.3	
25	0^+	5.2	60.9	94.6
	2^+	3.9	2.1	
50	0^+	19.8	70.8	74
	2^+	18.7	7.6	
75	0^+	31.9	90.2	66
	2^+	30.5	3.3	
100	0^+	14.8	79.8	88
	2^+	13.5	2.5	

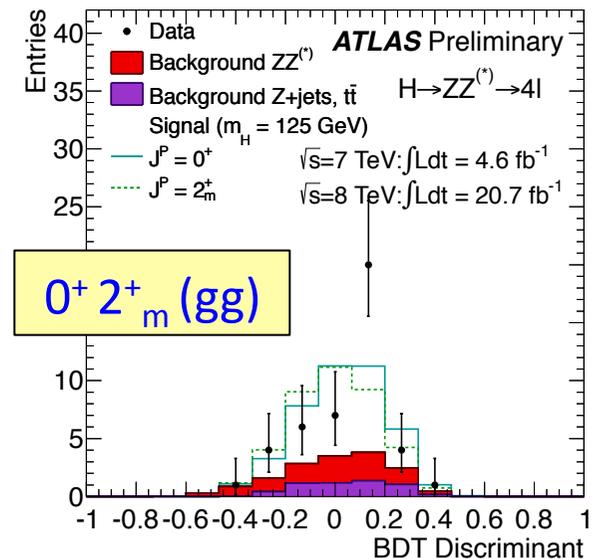
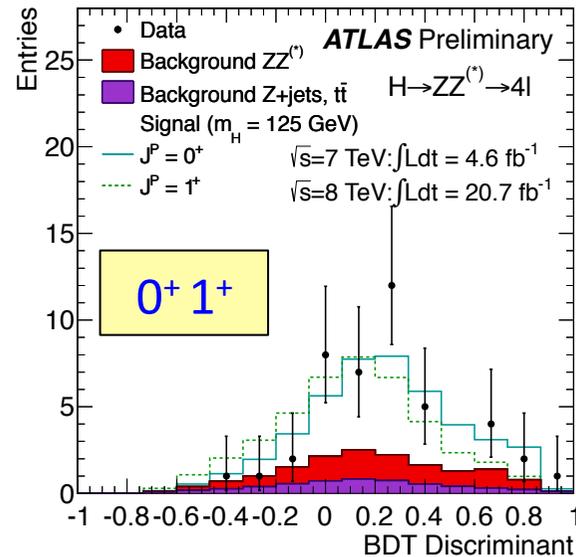
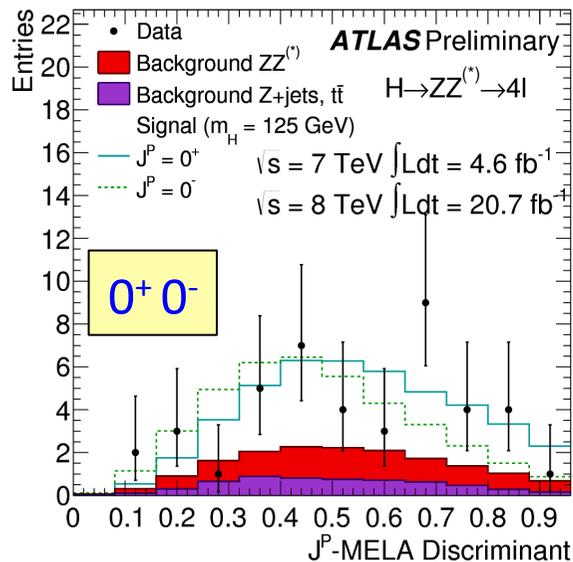




H \rightarrow ZZ \rightarrow 4l (ATLAS)

- Cut-based selection of 4l candidate events in the signal region: 115 GeV – 130 GeV.
- Two complimentary multivariate approaches for spin/parity measurements.
 - BDT analysis: discriminants trained to separate pairs of different Spin/CP states. Training on signal Monte Carlo after full reconstruction and selection.
 - J^P-MELA: discriminants based on the full Matrix Element analytical calculation for each Spin/CP hypothesis.
- Background: from full simulation (ZZ) and from control regions (others).

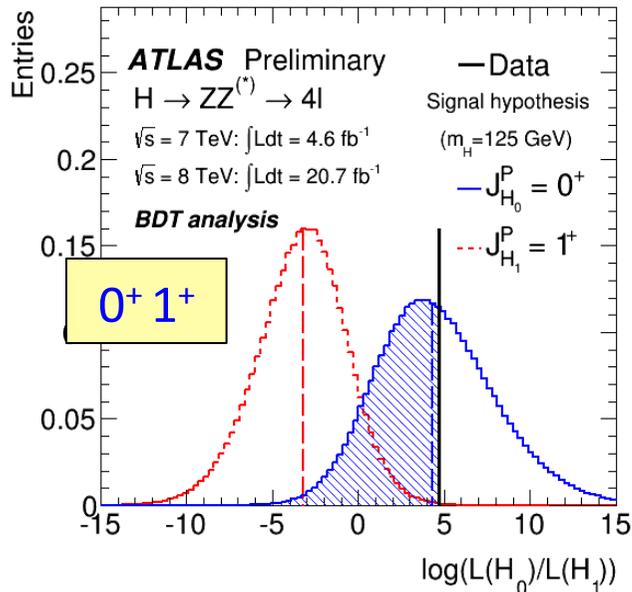
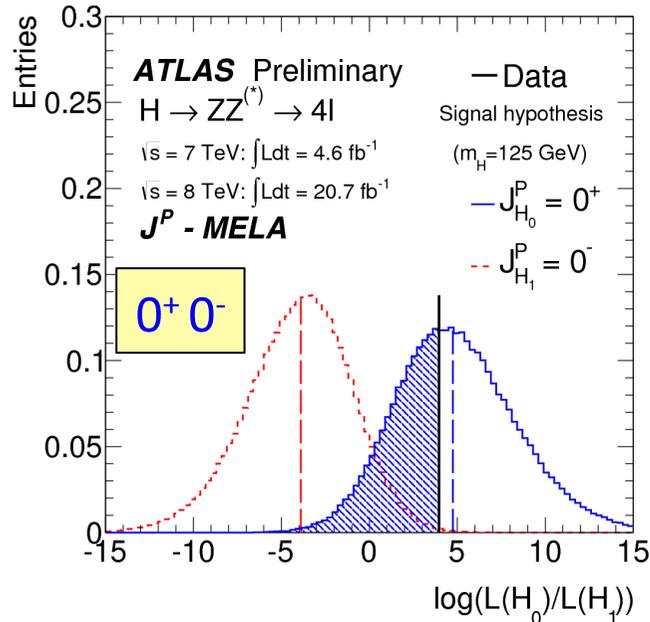
4.6 fb⁻¹ at 7 TeV and 20.7 fb⁻¹ at 8 TeV





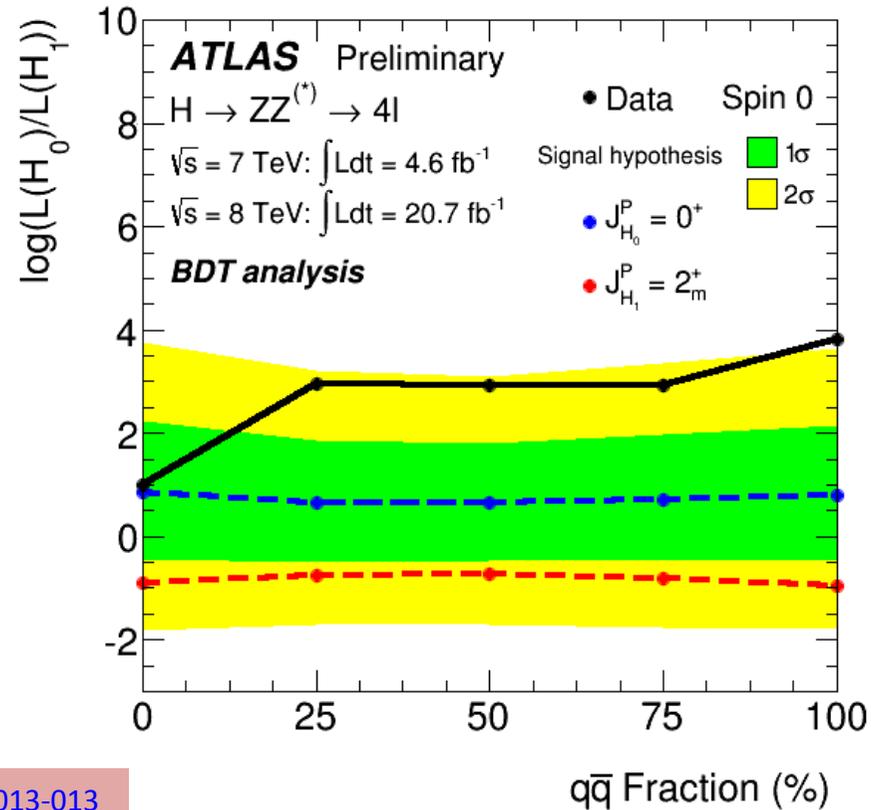
H → ZZ → 4l (ATLAS)

- Test statistic: ratio of profiled likelihoods.



Moderate, but stable expected separation between the Standard Model $J^P=0^+$ and $J^P=2^+_m$ hypotheses for all fractions of production mechanisms.

Observed data fluctuations due to low statistics.





H \rightarrow ZZ \rightarrow 4l (ATLAS)

μ from data	0 $^-$	1 $^+$	1 $^-$	2 ^+_m (gg)	2 $^-$
Expected p_0 (Alternative) BDT (J^P-MELA)	0.0037 (0.0011)	0.0016 (0.0031)	0.0038 (0.0010)	0.092 (0.064)	0.0053 (0.0032)
Observed p_0 (Alternative) BDT (J^P-MELA)	0.015 (0.0022)	0.001 (0.0028)	0.051 (0.027)	0.079 (0.11)	0.258 (0.11)
Observed $p_0(0^+)$ BDT (J^P-MELA)	0.31 (0.40)	0.55 (0.51)	0.15 (0.11)	0.53 (0.38)	0.037 (0.08)
Exclusion of hypothesis in favor of $J^P=0^+$, CL_s. BDT (J^P-MELA)	0.022 (0.003)	0.002 (0.005)	0.061 (0.030)	0.169 (0.182)	0.258 (0.115)

The results are consistent between BDT and J^P -MELA approaches. Data prefer $J^P=0^+$ over other hypotheses. Pseudo-scalar and spin-1 hypotheses are excluded at more than 95% CL.



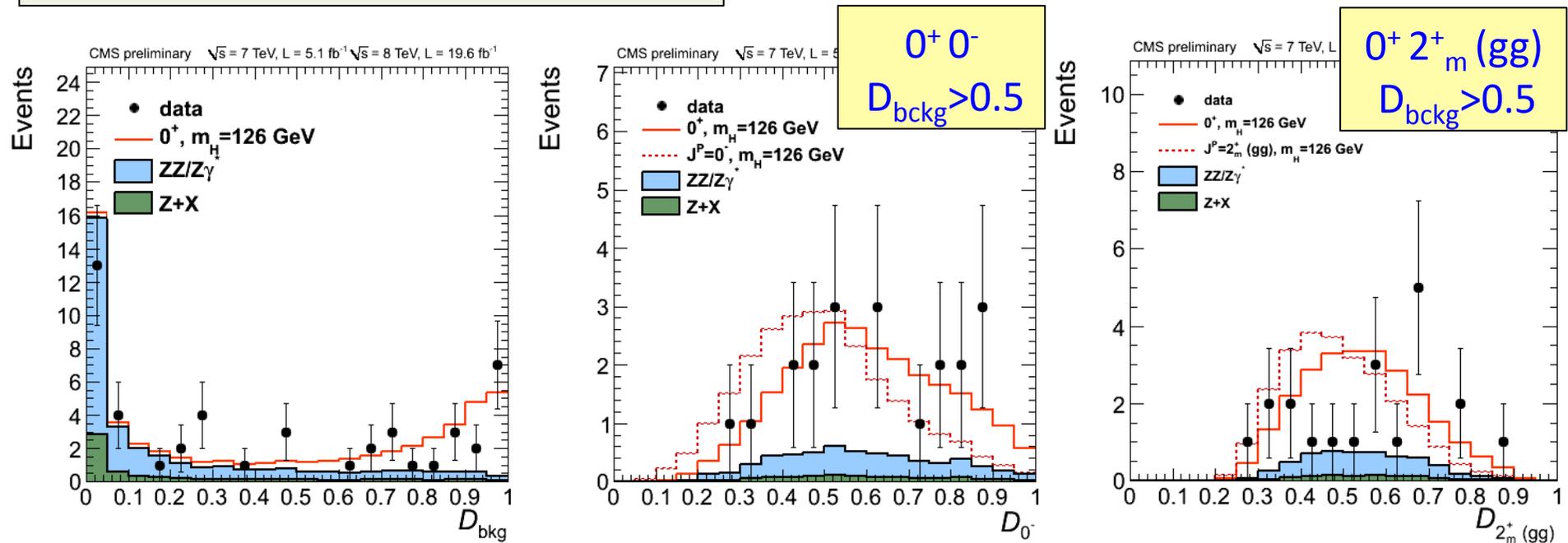
H \rightarrow ZZ \rightarrow 4l (CMS)

Discriminants based on the calculation of the matrix element:
one to separate pairs of spin-parity states (D_{JP}) and one to reject the ZZ
background: $D_{\text{bck}}(K_D, m_{4l})$.

2D analysis of the (D_{bck}, D_{JP}) distribution.

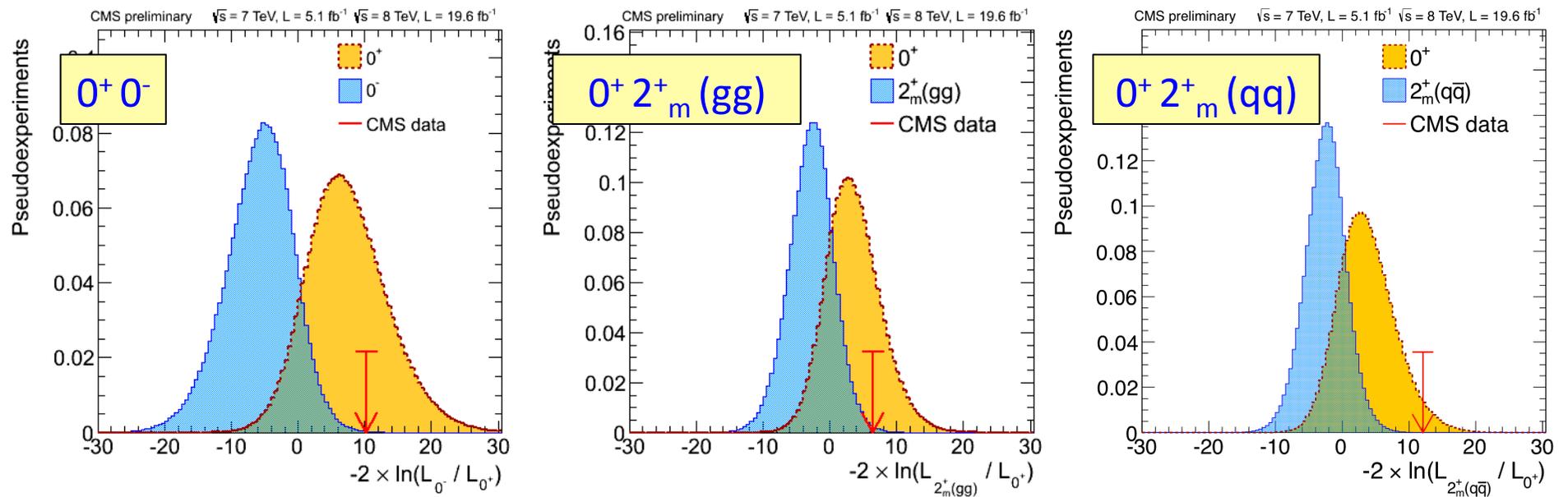
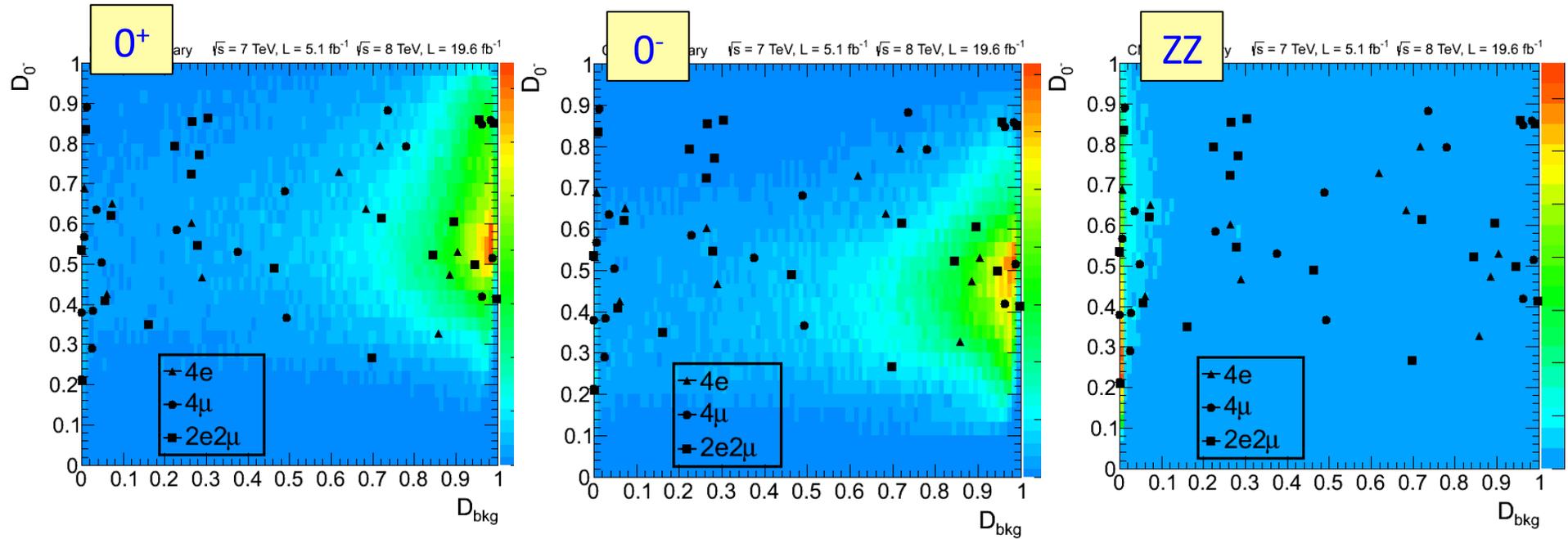
Considered spin and parity hypotheses: 0^+ , 0^+_{h} , 0^- , 1^+ , 1^- , 2^+_m for different
production mechanisms.

5.1 fb $^{-1}$ at 7 TeV; 19.6 fb $^{-1}$ at 8 TeV





Spin/Parity measurement in $H \rightarrow ZZ \rightarrow 4l$ (CMS)





H \rightarrow ZZ \rightarrow 4l (CMS)

	Expected [σ]		Observed (μ from data)		
	$\mu=1$	μ from data	P (alternative) [σ]	P (Standard Model Higgs) [σ]	CL _s [%]
gg \rightarrow 0 ⁻	2.8	2.6	3.3	-0.5	0.16
gg \rightarrow 0 ⁺ _h	1.8	1.7	1.7	0.0	8.1
qq \rightarrow 1 ⁺	2.6	2.3	>4.0	-1.7	<0.1
qq \rightarrow 1 ⁻	3.1	2.8	>4.0	-1.4	<0.1
gg \rightarrow 2 ⁺ _m	1.9	1.8	2.7	-0.8	1.5
qq \rightarrow 2 ⁺ _m	1.9	1.7	4.0	1.8	<0.1

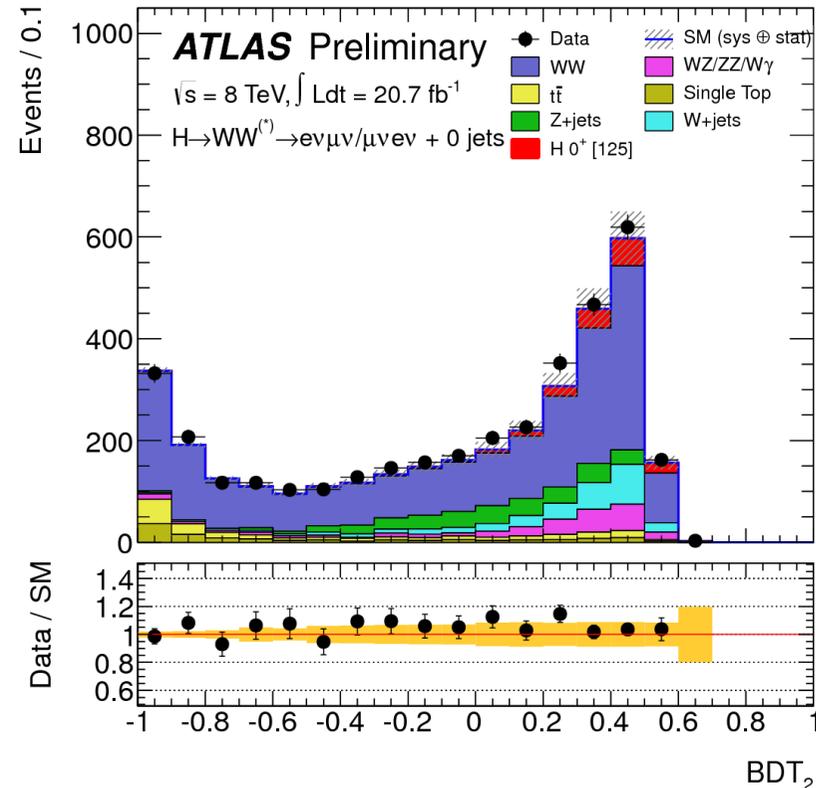
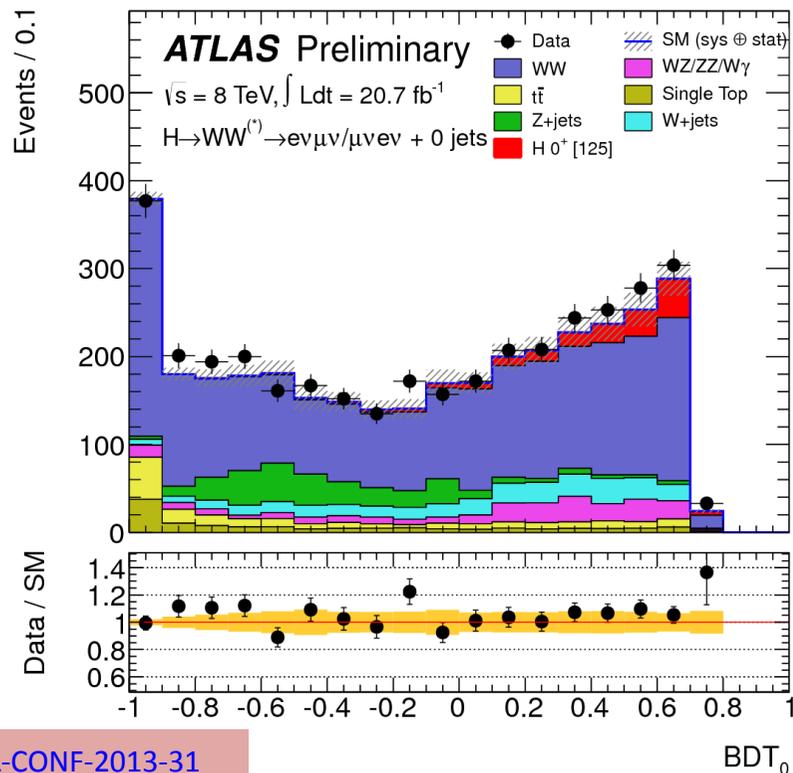
Studied pseudo-scalar, spin-1 and spin-2 models are excluded at 95% CL and higher.



H \rightarrow WW \rightarrow ev $_e$ μ v $_\mu$ (ATLAS)

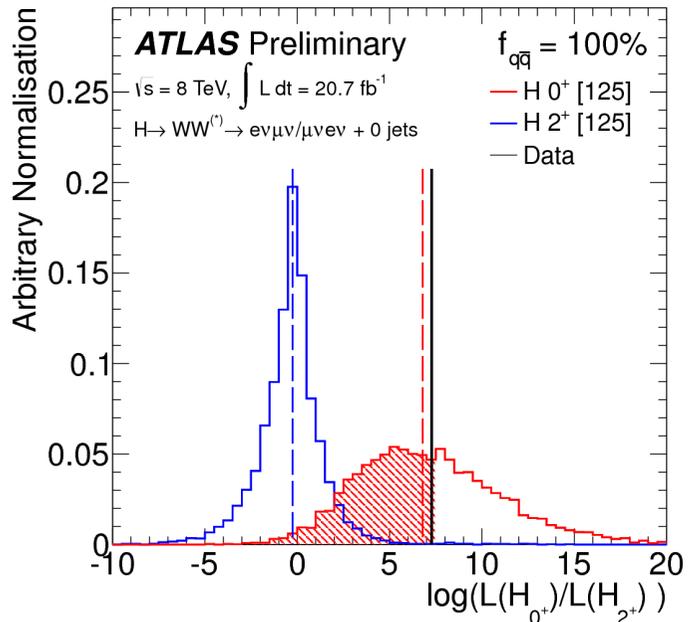
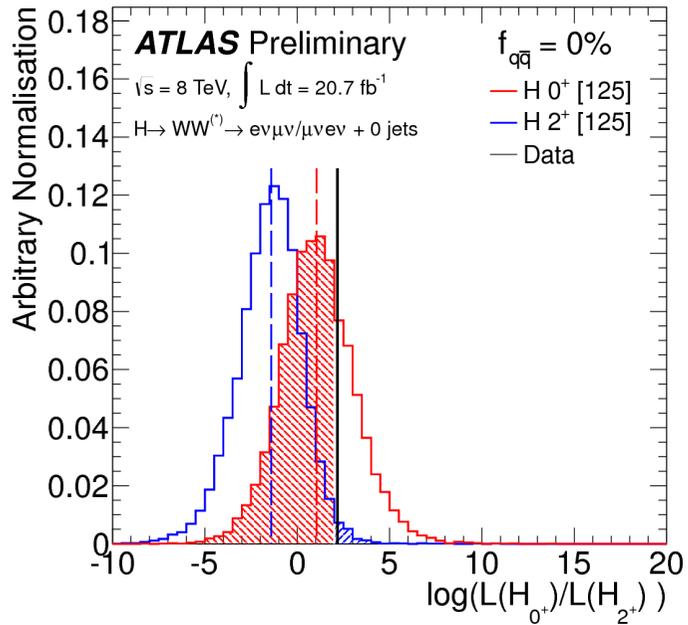
- Analysis uses the 0-jet e/μ channel only. Most sensitive to the spin due to the relatively low backgrounds.
 - Hypotheses: 0^+ and 2^+_{m}
- Spin-sensitive variables: m^{\parallel} , p^{\parallel}_{T} , $\Delta\phi^{\parallel}$ and m_{T} .
- Analysis method: two dimensional fit. Two BDT scores are calculated for each event: 0^+ or 2^+_{m} against background.

20.7 fb $^{-1}$ at 8 TeV
Different cuts from
'discovery' analysis.



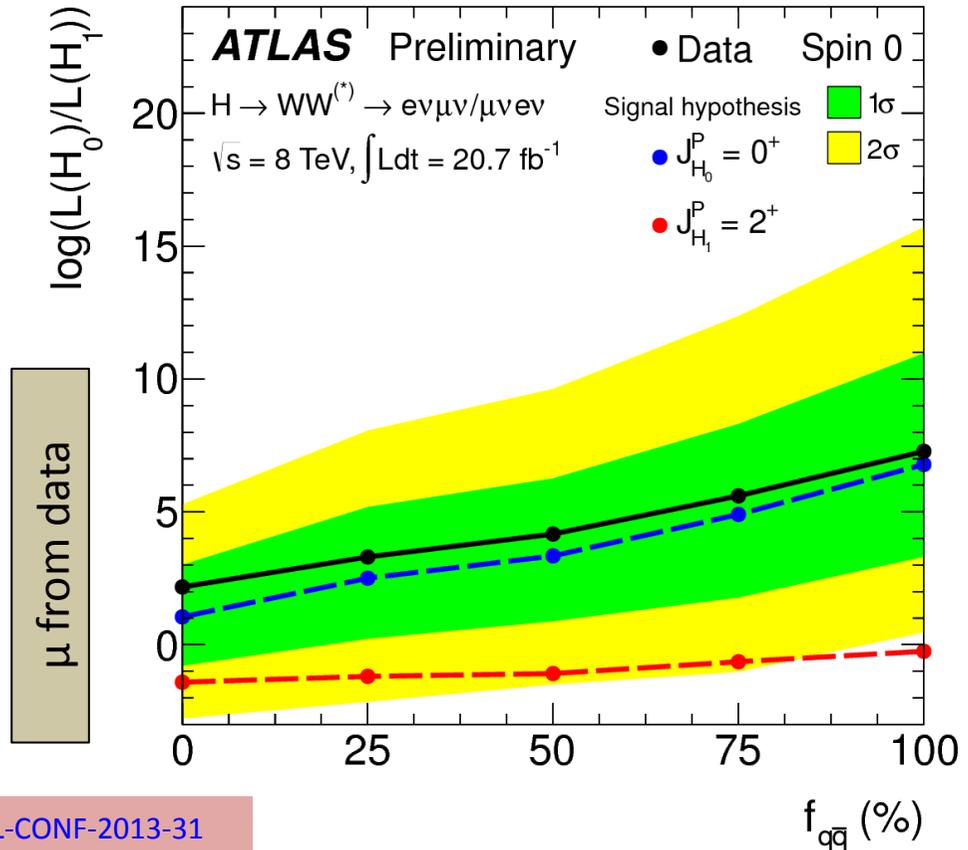


H → WW → eν_eμν_μ (ATLAS)



Separation between the Standard Model $J^P=0^+$ and $J^P=2^+$ hypotheses grows as the function of the $q\bar{q}$ fraction.

Observed exclusions: 95%CL to 99% CL in favor of the Standard Model $J^P=0^+$ hypothesis.





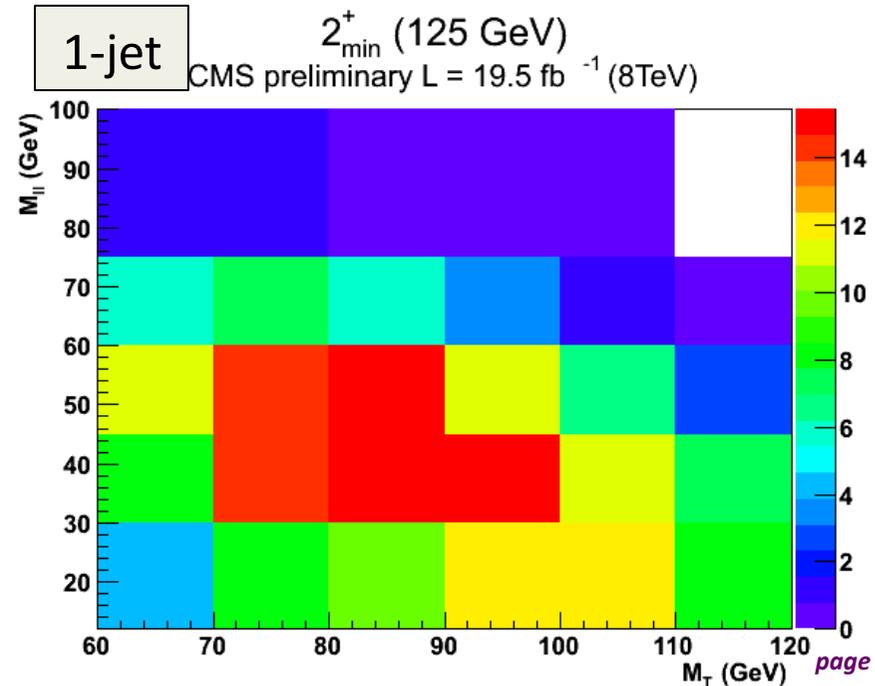
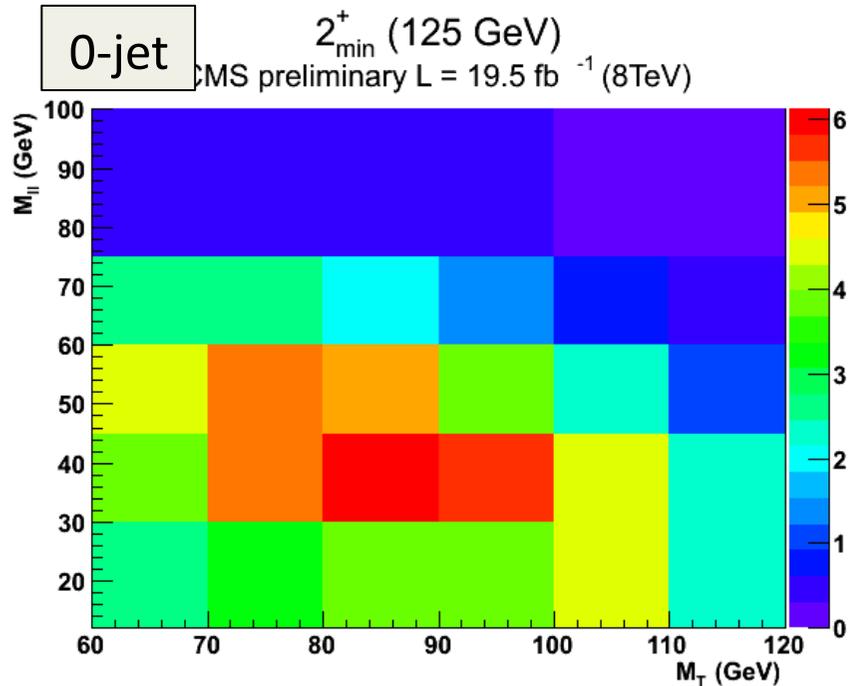
H- \rightarrow WW- \rightarrow l ν l ν (CMS)

Cut-based selection. Same configuration as for the search analysis.

Likelihood fit to two-dimensional templates: m_{ll} vs m_T . 0- and 1- jet categories.
Different lepton flavours.

Signal template: PowHeg (0+) and JHU (2^+_m). Background templates – same as main analysis (mostly control regions).

4.9 fb $^{-1}$ at 7 TeV and 19.5 fb $^{-1}$ at 8 TeV





H \rightarrow WW \rightarrow l ν l ν (CMS)

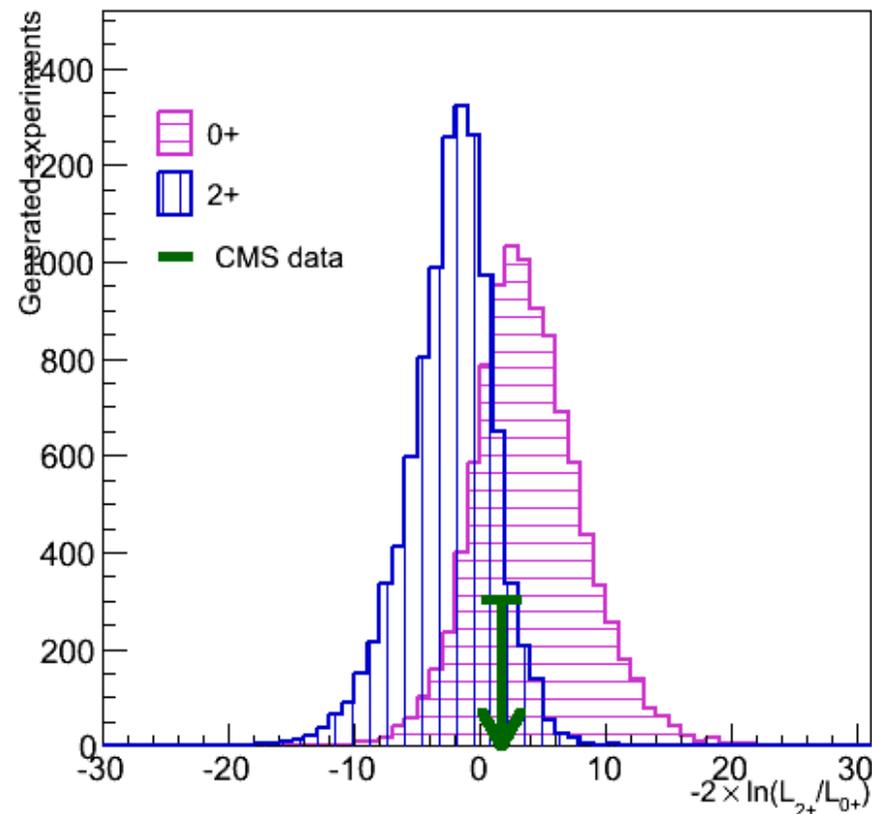
Assuming $\mu=1$, the observed q value is 0.9σ and 1.3σ away from away from the expected values for the 0^+ and 2^+_m (100% gg).

Taking μ from data, the observed q value is 0.5σ and 1.3σ away from the expected values for the 0^+ and 2^+_m (100% gg)

μ from data.

The 2^+_m (100% gg) hypothesis is disfavored with CLS of 14 %

CMS Preliminary $\sqrt{s} = 7 \text{ TeV}, L = 4.9 \text{ fb}^{-1}; \sqrt{s} = 8 \text{ TeV}, L = 19.5 \text{ fb}^{-1}$





Spin and parity sensitivity summary

CMS	ZZ	WW
0^-	2.8	
1^+	2.6	
1^-	3.1	
2^+_m (gg)	1.9	1.9
2^+_m (qq)	1.9	

ATLAS	ZZ	WW	$\gamma\gamma$
0^-	3.1		
1^+	2.7		
1^-	3.1		
2^+_m (gg)	1.5	1.6	2.6
2^+_m (qq)	1.5	2.6	

Expected exclusion of alternative hypothesis in favor of the Standard Model $J^P=0^+$.

CMS: number of standard deviations assuming $\mu=1$. 5.1 fb^{-1} at 7 TeV; 19.6 fb^{-1} at 8 TeV for both channels

ATLAS number of standard deviations taking μ from data. 20.7 fb^{-1} at 8 TeV for WW and $\gamma\gamma$; Additional 4.6 fb^{-1} at 7 TeV for the ZZ.

(Very naive) extrapolation of spin-2 exclusion in ZZ channel to the 300 fb^{-1} at 14 TeV:

About 8 (ATLAS) – 10 (CMS) σ .

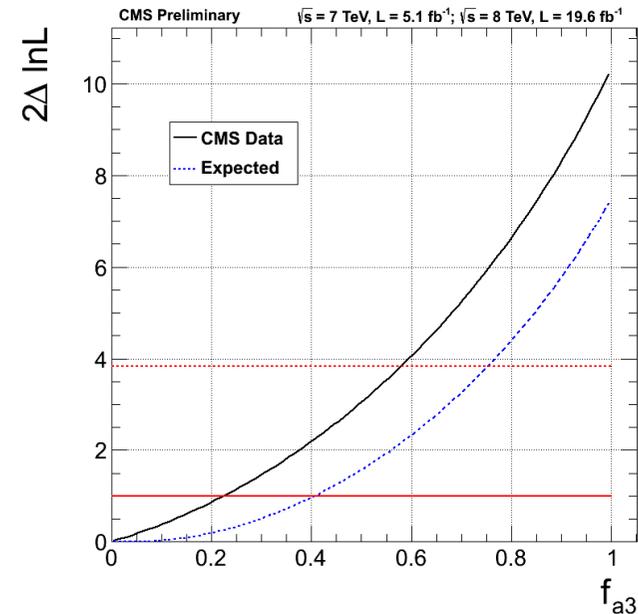
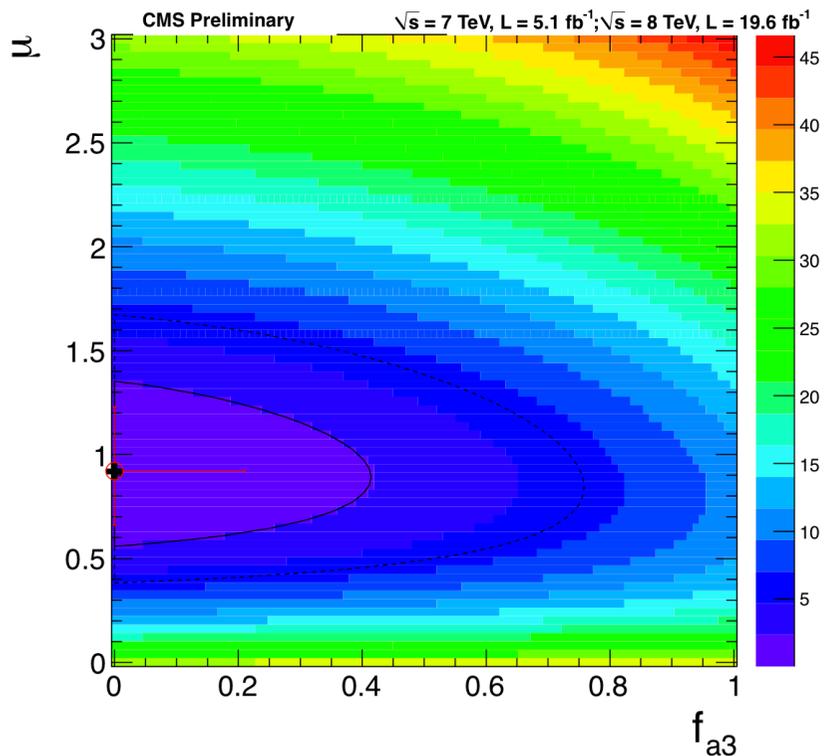


CP-mixing in $H \rightarrow ZZ \rightarrow 4l$ (CMS)

Scan of 2 times the log-likelihood ratio between the two signal models as a function of the signal strength and f_{a3} , the fraction of observed 0^- events in the dataset.

$$A = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*v} \left(a_1 g_{\mu\nu} m_H^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right) = A_1 + A_2 + A_3,$$

$$f_{a3} = |A_3|^2 / (|A_1|^2 + |A_3|^2).$$



5.1 fb^{-1} at 7 TeV + 19.6 fb^{-1} at 8 TeV
 $f_{a3} < 0.58$ at 95% CL

Projection for 300 (3000) fb^{-1}
 (Snowmass Higgs workshop in Princeton):
 2σ exclusion of $f_{a3} > 0.15$ (0.05)



European Strategy (ATLAS)

$$A(X \rightarrow VV) \sim \underbrace{(a_1 M_X^2 g_{\mu\nu})}_{\text{CP-even}} + \underbrace{a_2 (q_1 + q_2)_\mu (q_1 + q_2)_\nu}_{\text{CP-odd}} + \underbrace{a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta}_{\text{CP-odd}} \epsilon_1^{*\mu} \epsilon_2^{*\nu}$$

- Choose the form factor $a_1 = 1, a_2 = 0$ and vary a_3 .
 - H->ZZ(*)->4l BDT analysis.
- Generator level Monte Carlo study. JHU at 14 TeV for the signal and MadGraph for the ZZ background. Pythia showering (AU2 CTEQ6L1).
- Smearing functions to simulate detector resolution effects. Trigger and reconstruction efficiencies are accounted for by assigning event weights.

	Exclusion $a_3 = 6+6i$ ($f_{a3} > 0.63$)	Exclusion $a_3 = 6i$ ($f_{a3} > 0.46$)	Exclusion $a_3 = 4+4i$ ($f_{a3} > 0.43$)
100 fb ⁻¹	3.0	2.4	2.2
200 fb ⁻¹	4.2	3.3	3.1
300 fb ⁻¹	5.2	4.1	3.8

Exclusion (N standard deviations) of CP-violating contribution in favor of the Standard Model $J^P=0^+$

Uncertainty on f_{a3} approx. 0.1 at 300 fb⁻¹



Summary

- First spin and parity results have been published by ATLAS and CMS.
 - The data prefer $J^P=0^+$.
 - Most of considered alternative hypotheses excluded at 95% CL – 99% CL.
- CP-mixing:
 - First limits on the observed CP-even-CP-odd mixing published by CMS.
 - Projection to 300(3000) fb^{-1} : of $f_{a3} > 0.15$ (0.05) at 95 % CL.
 - ATLAS study shows that the exclusion of large CP-violating couplings will require hundreds of fb^{-1} .
- Further studies of the 23.3 fb^{-1} at 8 TeV + 5.6 fb^{-1} at 7 TeV dataset and beyond:
 - Start working with VBF $H \rightarrow \gamma\gamma$, VH $H \rightarrow bb$.
- Snowmass study: to estimate the amount of data required to set limits on the f_{a3} . Interpretation in terms of mixing angle?



Backup



Data taking in 2011 and 2012

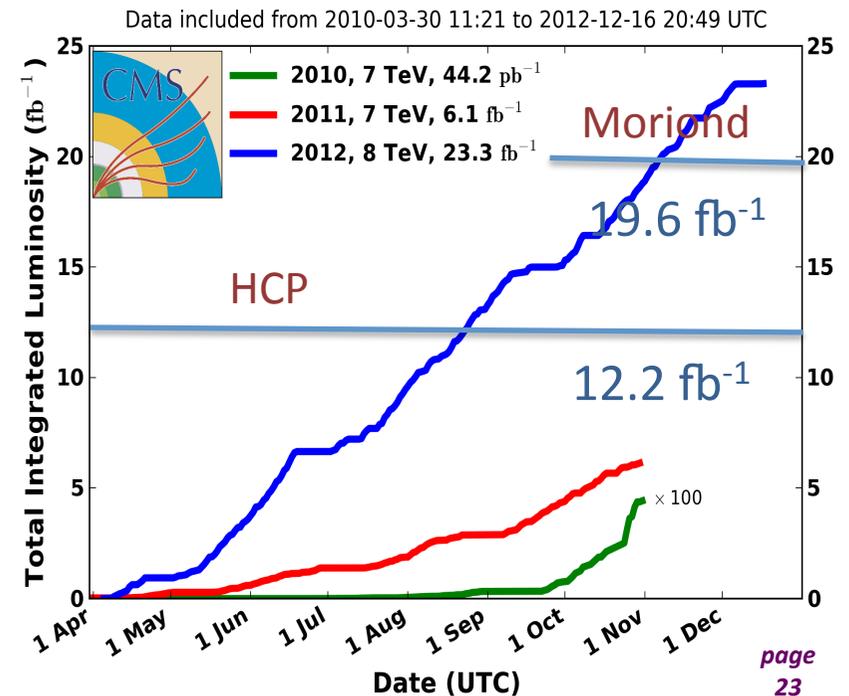
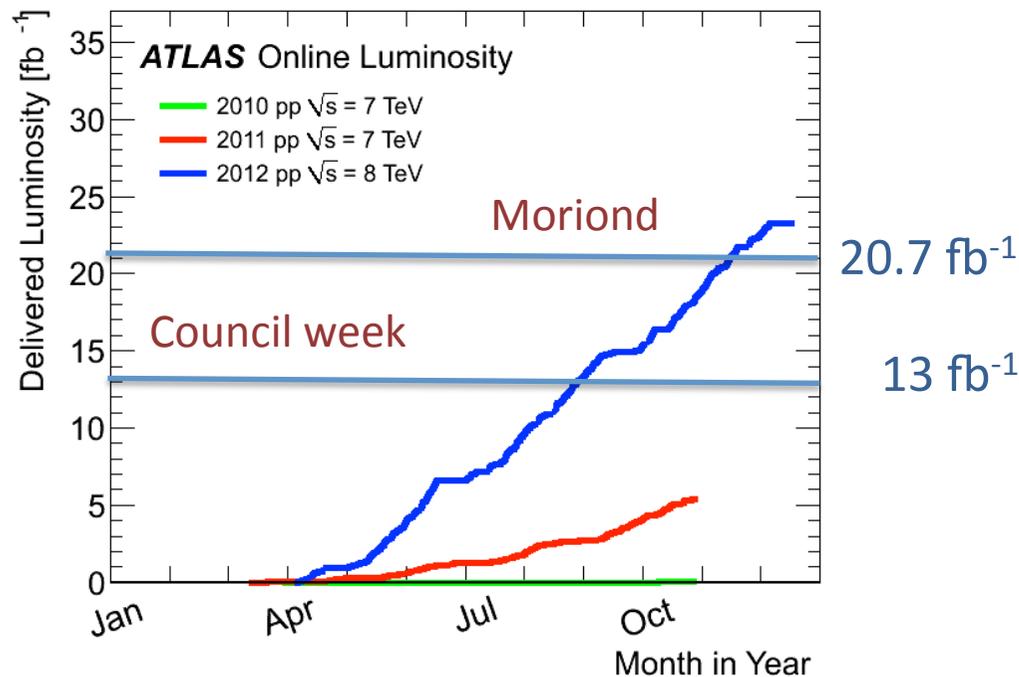
ATLAS

	\sqrt{s}	Delivered (fb^{-1})	Recorded (fb^{-1})
pp 2011	7 TeV	5.61	5.25
pp 2012	8 TeV	23.3	21.7

CMS

	\sqrt{s}	Delivered (fb^{-1})	Recorded (fb^{-1})
pp 2011	7 TeV	6.1	5.55
pp 2012	8 TeV	23.3	21.79

CMS Integrated Luminosity, pp





Considered search channels (ATLAS)

Higgs Boson Decay	Subsequent Decay	Sub-Channels	$\int L dt$ [fb ⁻¹]	Ref.
2011 $\sqrt{s} = 7$ TeV				
$H \rightarrow ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	4.6	[10]
$H \rightarrow \gamma\gamma$	–	10 categories $\{p_{Tl} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{2\text{-jet VBF}\}$	4.8	[9]
$H \rightarrow \tau\tau$	$\tau_{lep}\tau_{lep}$	$\{e\mu\} \otimes \{0\text{-jet}\} \oplus \{\ell\ell\} \otimes \{1\text{-jet, 2-jet, } p_{T,\tau\tau} > 100 \text{ GeV, } VH\}$	4.6	[11]
	$\tau_{lep}\tau_{had}$	$\{e, \mu\} \otimes \{0\text{-jet, 1-jet, } p_{T,\tau\tau} > 100 \text{ GeV, 2-jet}\}$	4.6	
	$\tau_{had}\tau_{had}$	$\{1\text{-jet, 2-jet}\}$	4.6	
$VH \rightarrow Vbb$	$Z \rightarrow \nu\nu$	$E_T^{miss} \in \{120 - 160, 160 - 200, \geq 200 \text{ GeV}\} \otimes \{2\text{-jet, 3-jet}\}$	4.6	[12]
	$W \rightarrow \ell\nu$	$p_T^W \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	4.7	
	$Z \rightarrow \ell\ell$	$p_T^Z \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	4.7	
2012 $\sqrt{s} = 8$ TeV				
$H \rightarrow ZZ^{(*)}$	4ℓ	$\{4e, 2e2\mu, 2\mu2e, 4\mu\}$	20.7	[10]
$H \rightarrow \gamma\gamma$	–	14 categories $\{p_{Tl} \otimes \eta_\gamma \otimes \text{conversion}\} \oplus \{2\text{-jet VBF}\} \oplus \{\ell\text{-tag, } E_T^{miss}\text{-tag, 2-jet VH}\}$	20.7	[9]
$H \rightarrow WW^{(*)}$	$e\nu\mu\nu$	$\{e\mu, \mu e\} \otimes \{0\text{-jet, 1-jet}\}$	13	[13]
$H \rightarrow \tau\tau$	$\tau_{lep}\tau_{lep}$	$\{\ell\ell\} \otimes \{1\text{-jet, 2-jet, } p_{T,\tau\tau} > 100 \text{ GeV, } VH\}$	13	[11]
	$\tau_{lep}\tau_{had}$	$\{e, \mu\} \otimes \{0\text{-jet, 1-jet, } p_{T,\tau\tau} > 100 \text{ GeV, 2-jet}\}$	13	
	$\tau_{had}\tau_{had}$	$\{1\text{-jet, 2-jet}\}$	13	
$VH \rightarrow Vbb$	$Z \rightarrow \nu\nu$	$E_T^{miss} \in \{120 - 160, 160 - 200, \geq 200 \text{ GeV}\} \otimes \{2\text{-jet, 3-jet}\}$	13	[12]
	$W \rightarrow \ell\nu$	$p_T^W \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	13	
	$Z \rightarrow \ell\ell$	$p_T^Z \in \{< 50, 50 - 100, 100 - 150, 150 - 200, \geq 200 \text{ GeV}\}$	13	

“Moriond EW”
data set.

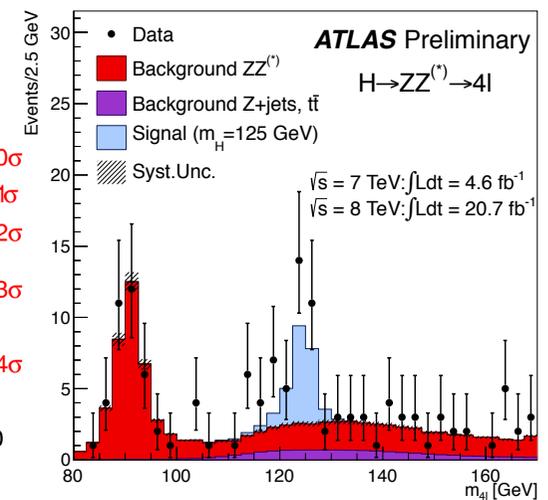
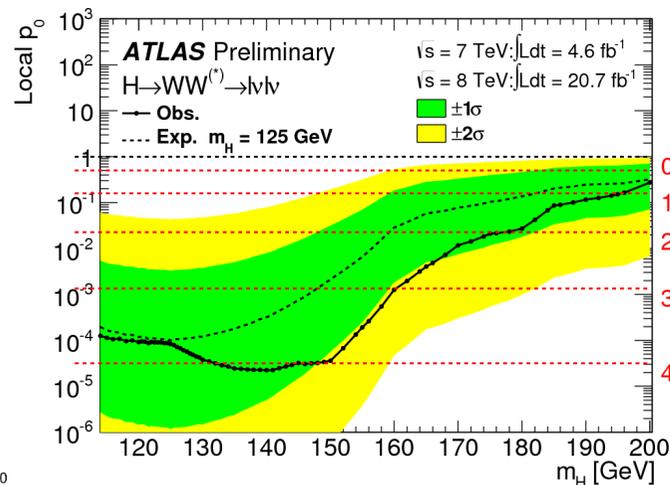
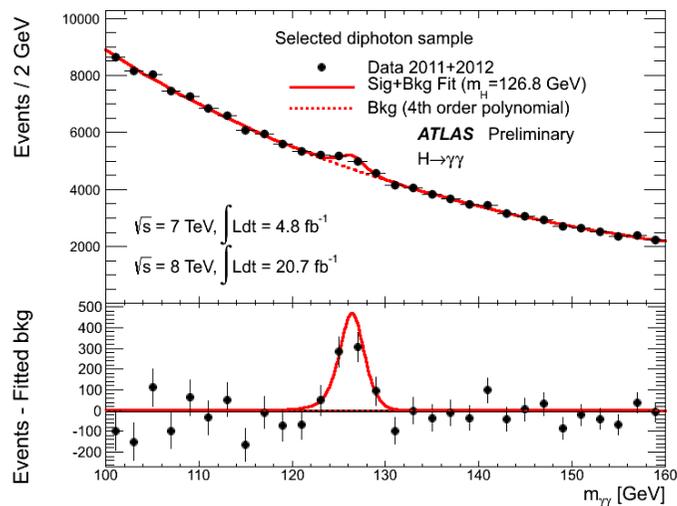
“Council week”
data set.

- Current status of analysis in the individual channels where the searches were performed.
- Final result is the combination of all considered modes.
- Search performed in the range $m_H = 110 - 600$ GeV.



Status of the new resonance (ATLAS)

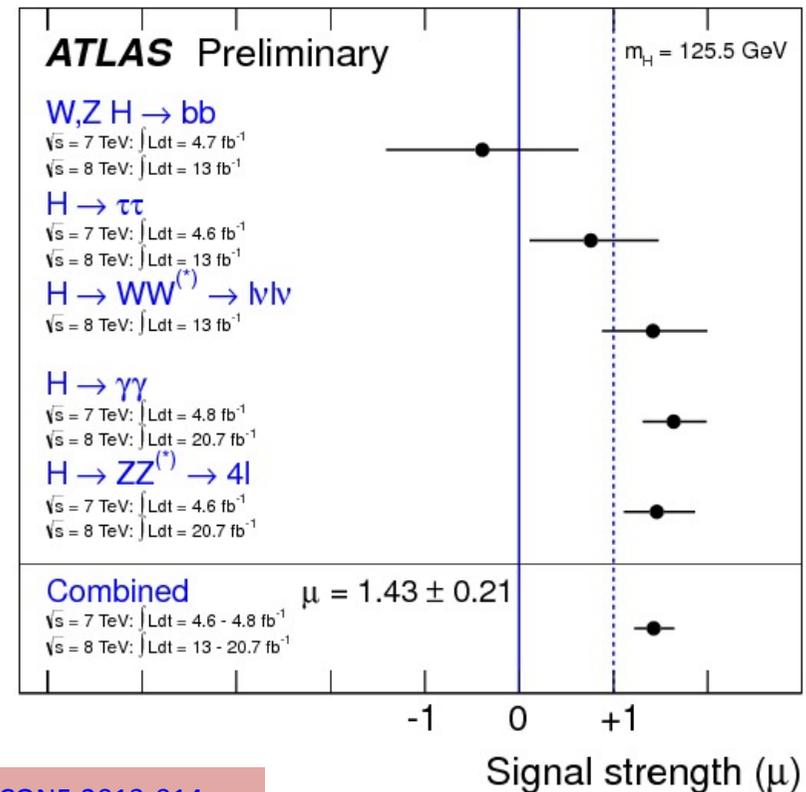
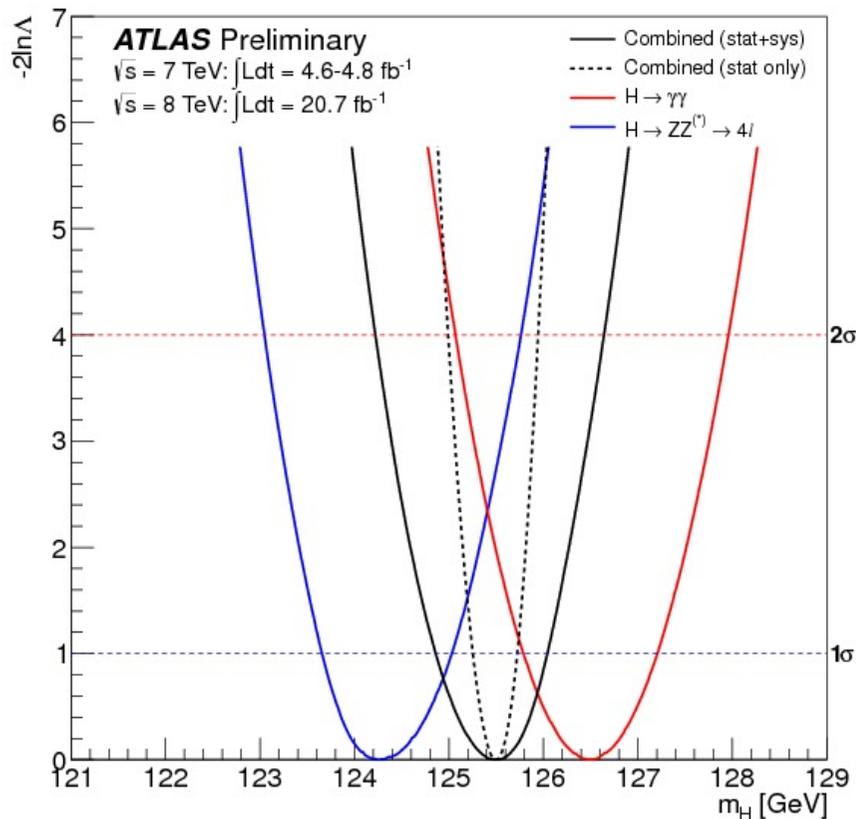
- In February-March 2013, the ZZ, $\gamma\gamma$ and WW results were updated with larger data sets
 - Up to 20.7 fb⁻¹ at 8 TeV + 4.6 fb⁻¹ at 7 TeV.
- Individual local significance of excess reached 7.4 ($\gamma\gamma$), 6.8 (ZZ) and 3.8 (WW) standard deviations.





Status of the new resonance (ATLAS)

- Combined mass measurement from $H \rightarrow ZZ^{(*)} \rightarrow 4l$, $H \rightarrow \gamma\gamma$ channels:
 $m_H = 125.5 \pm 0.2$ (stat) $^{+0.5}_{-0.6}$ (sys) GeV.
- The mass difference between two channels:
 $\Delta m_H = 2.3^{+0.6}_{-0.7}$ (stat) ± 0.6 (sys) GeV.
 - Corresponds to probability of 1.5% (2.4 standard deviations).





Status of the new resonance (CMS)

$H \rightarrow ZZ^{(*)} \rightarrow 4l$: 3D analysis using matrix element-based kinematic discriminant for each m_{4l} .

$m_H = 125.8 \pm 0.5(\text{stat.}) \pm 0.2(\text{syst.}) \text{ GeV}$

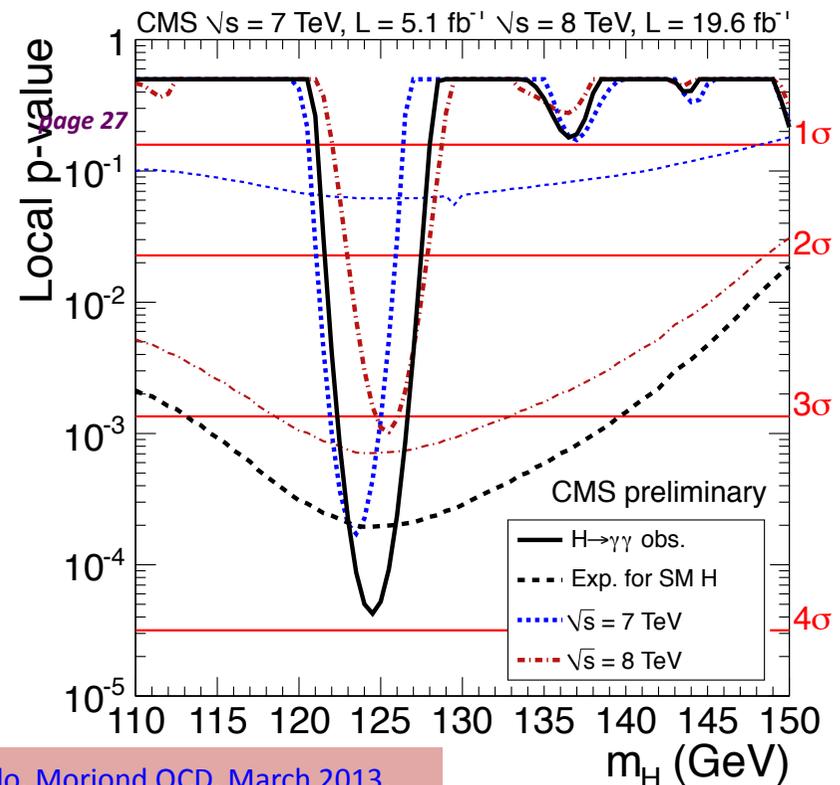
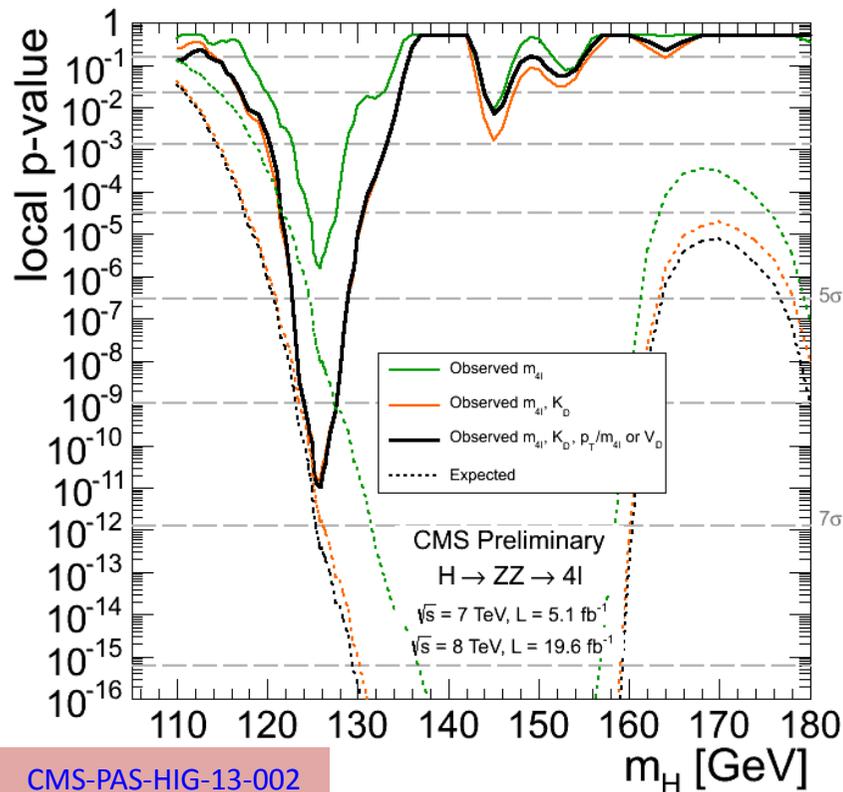
$\mu = 0.91^{+0.30}_{-0.24}$

$H \rightarrow \gamma\gamma$: cut-based and MVA analyses. Statistically compatible ($< 2\sigma$).

Significance (Moriond): 3.2σ (4.2 exp)

$m_H = 125.4 \pm 0.5 (\text{stat.}) \pm 0.6 (\text{syst.})$

$H \rightarrow WW$: 4σ significance





Spin-2 models

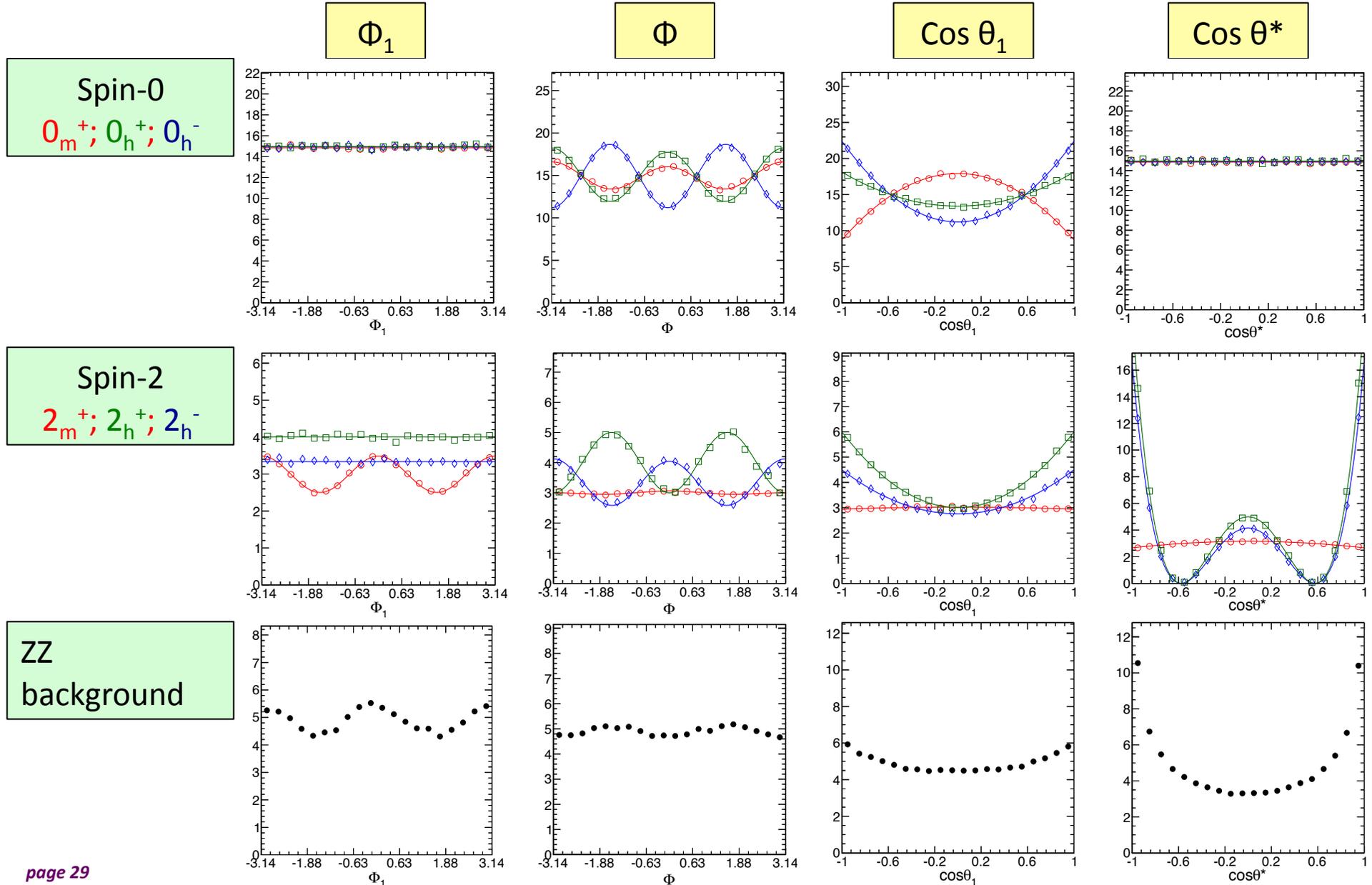
$$\begin{aligned}
 A(X \rightarrow V_1 V_2) = \Lambda^{-1} & \left[\underline{2g_1 X_{\mu\nu} f^{*(1)\mu\alpha} f_{\alpha}^{*(2)\nu}} \right. \\
 & + 2g_2 X_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3 \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} X_{\beta\nu} \left(f^{*(1)\mu\nu} f_{\mu\alpha}^{*(2)} + f^{*(2)\mu\nu} f_{\mu\alpha}^{*(1)} \right) \\
 & + g_4 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} X_{\mu\nu} f^{*(1)\alpha\beta} f_{\alpha\beta}^{*(2)} + m_v^2 X_{\mu\nu} \left(\underline{2g_5 \varepsilon_1^{*\mu} \varepsilon_2^{*\nu}} + 2g_6 \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} (\varepsilon_1^{*\nu} \varepsilon_2^{*\alpha} - \varepsilon_1^{*\alpha} \varepsilon_2^{*\nu}) + g_7 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} (\varepsilon_1^* \varepsilon_2^*) \right) \\
 & \left. + g_8 \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} X_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}_{\alpha\beta}^{*(2)} + m_v^2 X_{\mu\alpha} \tilde{q}^\alpha \varepsilon_{\mu\nu\rho\sigma} \left(g_9 \frac{q^\sigma}{\Lambda^2} \varepsilon_1^{*\nu} \varepsilon_2^{*\rho} + g_{10} \frac{q^\rho \tilde{q}^\sigma}{\Lambda^4} (\varepsilon_1^{*\nu} (q\varepsilon_2^*) + \varepsilon_2^{*\nu} (q\varepsilon_1^*)) \right) \right] \quad (3)
 \end{aligned}$$

- The interaction of a spin-two particle with a pair of electroweak gauge bosons is described by at least 10 independent tensor couplings.
- General idea:
 - Given the number of possibilities, we cannot exclude ‘generic’ spin-2.
 - We should start with the model with minimal couplings and exclude it in favor of the SM hypothesis, which is relatively well defined.
 - If during this study we observe something ‘funny’ – have a deeper look in spin-2 models.
 - It is possible that both ggF and qq production mechanisms contribute to the spin-2 state. The possible mixtures should thus be studied.



Distributions of the Spin/CP sensitive variables

Examples of signal and background distributions as shown in arXiv:[1208.4018v1](https://arxiv.org/abs/1208.4018v1).





Distributions of the Spin/CP sensitive variables

Examples of signal and background distributions at the generator level.

Spin-0: 0^+ ; 0^-

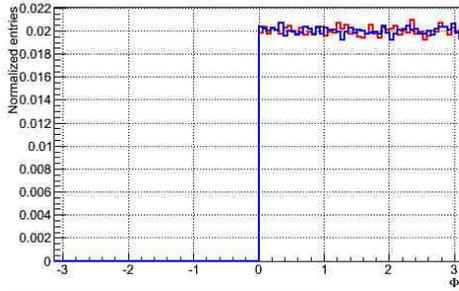
Φ_1

Φ

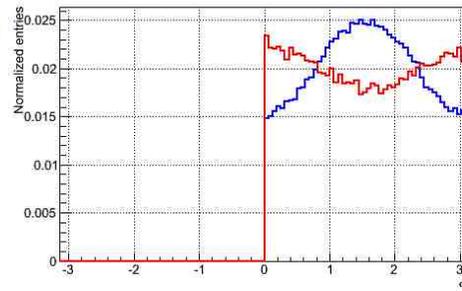
$\text{Cos } \theta_1$

$\text{Cos } \theta^*$

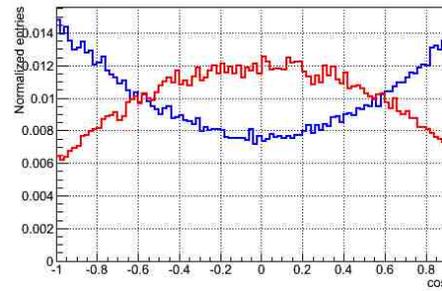
pp->H->ZZ->4l MH=125 GeV Spin=0 E=8 TeV



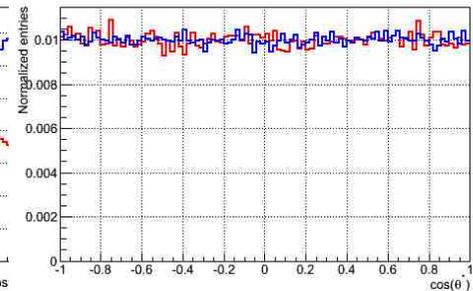
pp->H->ZZ->4l MH=125 GeV Spin=0 E=8 TeV



pp->H->ZZ->4l MH=125 GeV Spin=0 E=8 TeV

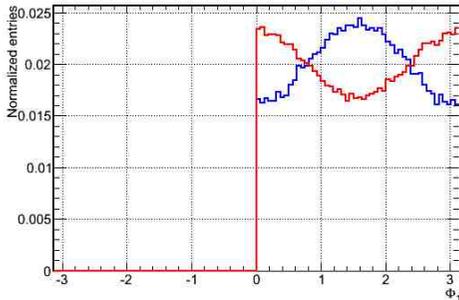


pp->H->ZZ->4l MH=125 GeV Spin=0 E=8 TeV

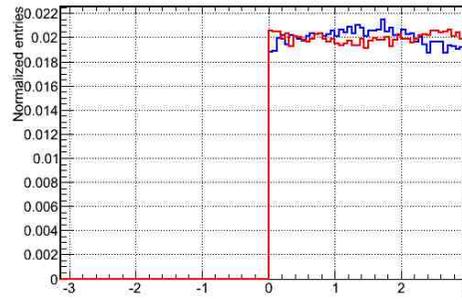


Spin-2: 2_m^+ ; 2^-

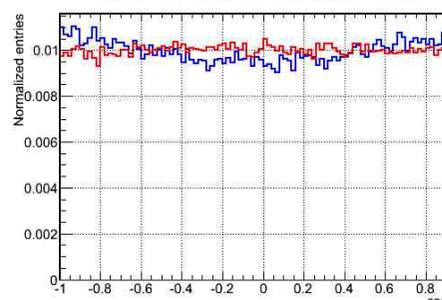
pp->H->ZZ->4l MH=125 GeV 2-8 TeV



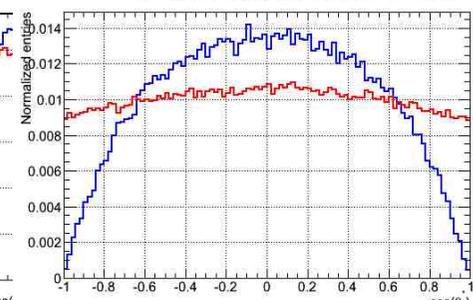
pp->H->ZZ->4l MH=125 GeV 2-8 TeV



pp->H->ZZ->4l MH=125 GeV Spin=2 E=8 TeV



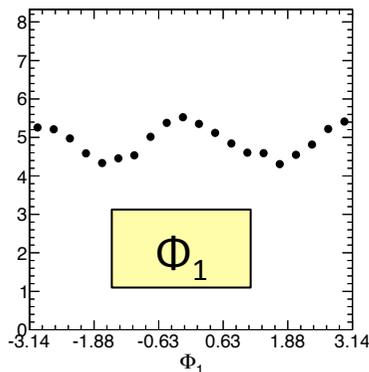
pp->H->ZZ->4l MH=125 GeV Spin=2 E=8 TeV



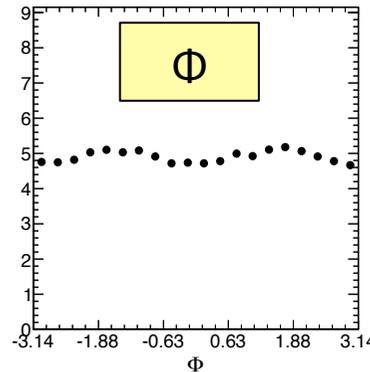
ZZ background

arXiv:

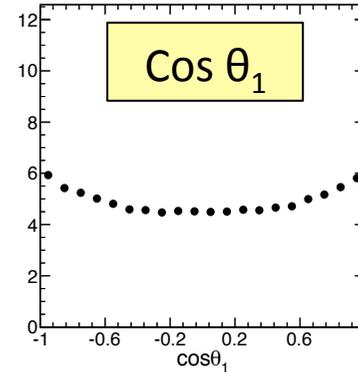
[1208.4018v1](https://arxiv.org/abs/1208.4018v1)



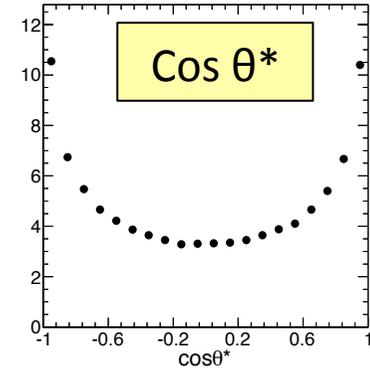
Φ



$\text{Cos } \theta_1$



$\text{Cos } \theta^*$





Distributions of the Spin/CP sensitive variables

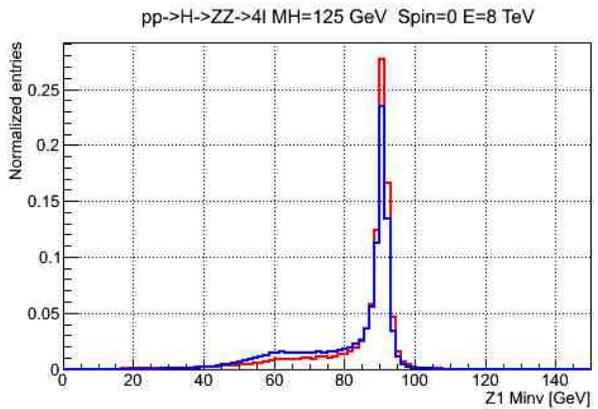
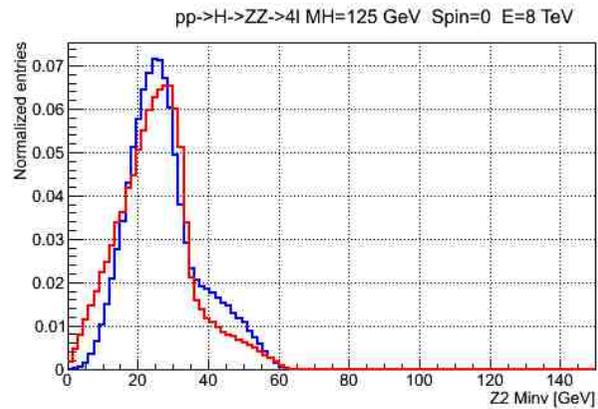
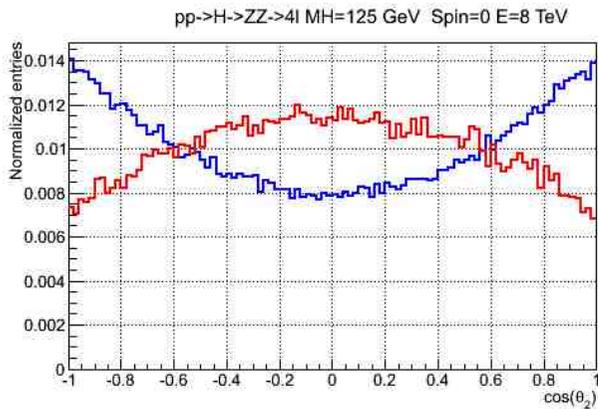
Examples of signal and background distributions at the generator level.

Spin-0: 0^+ ; 0^-

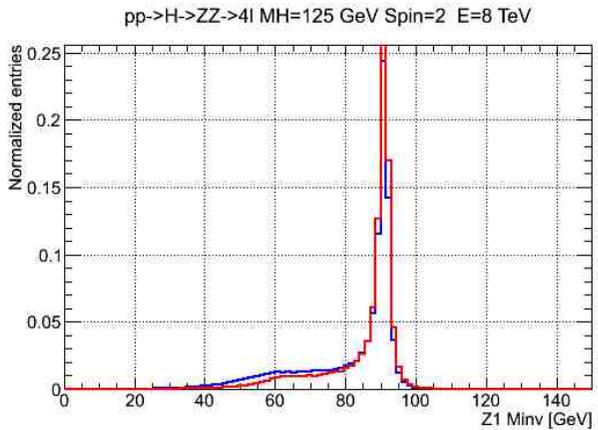
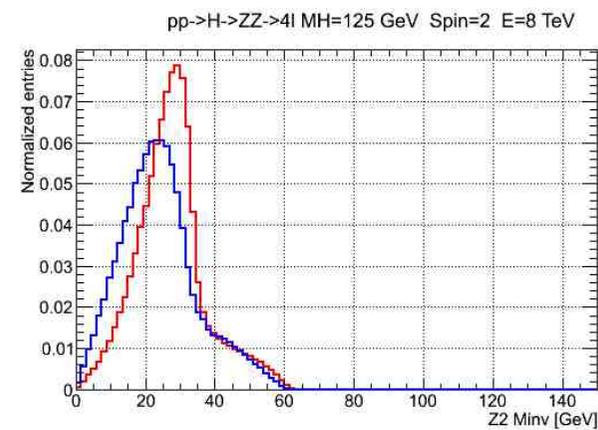
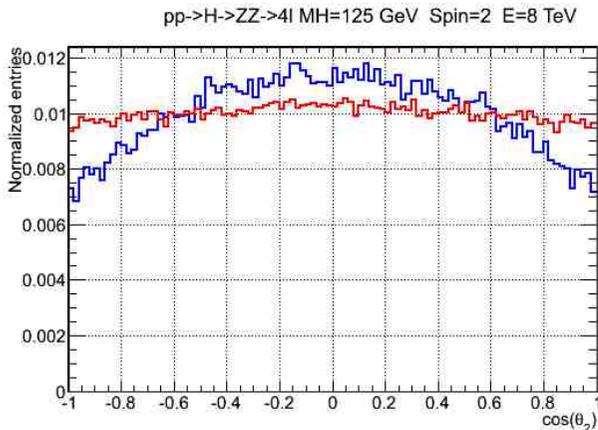
$\cos \theta_2$

m_{Z2}

m_{Z1}



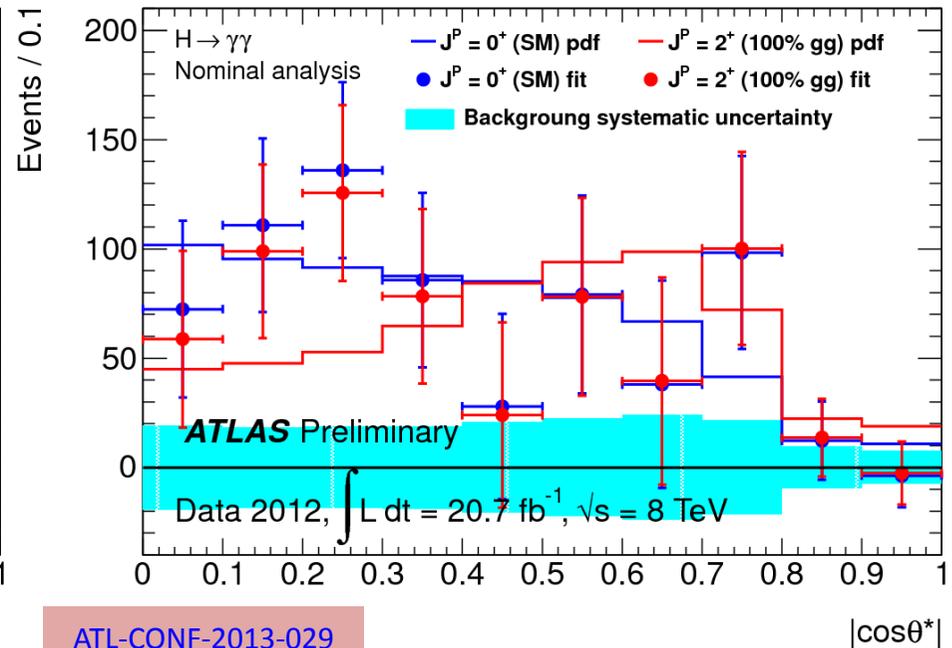
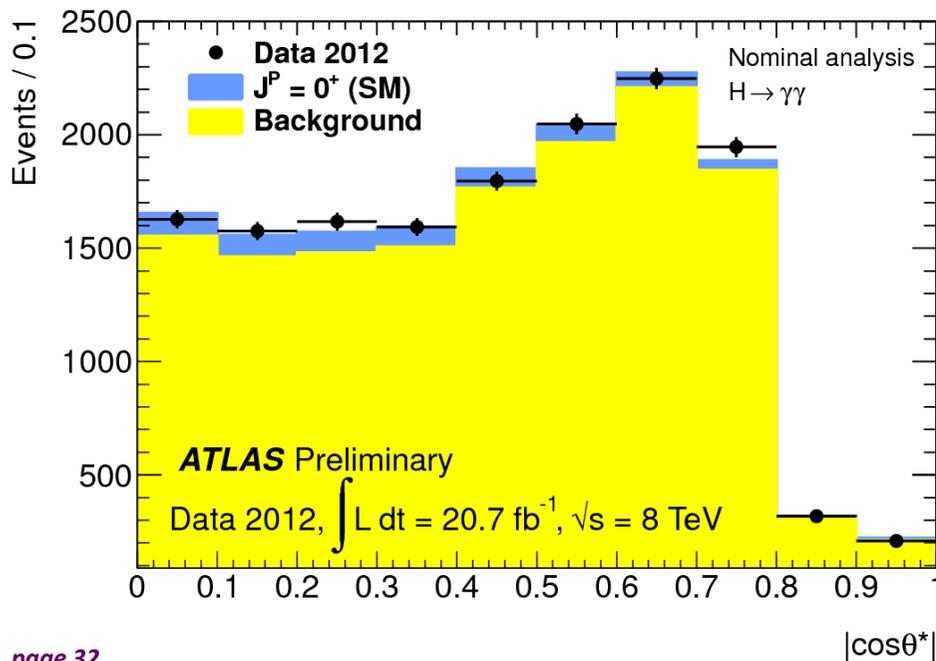
Spin-2: 2_m^+ ; 2^-





Spin measurements in $H \rightarrow \gamma\gamma$ decay (ATLAS)

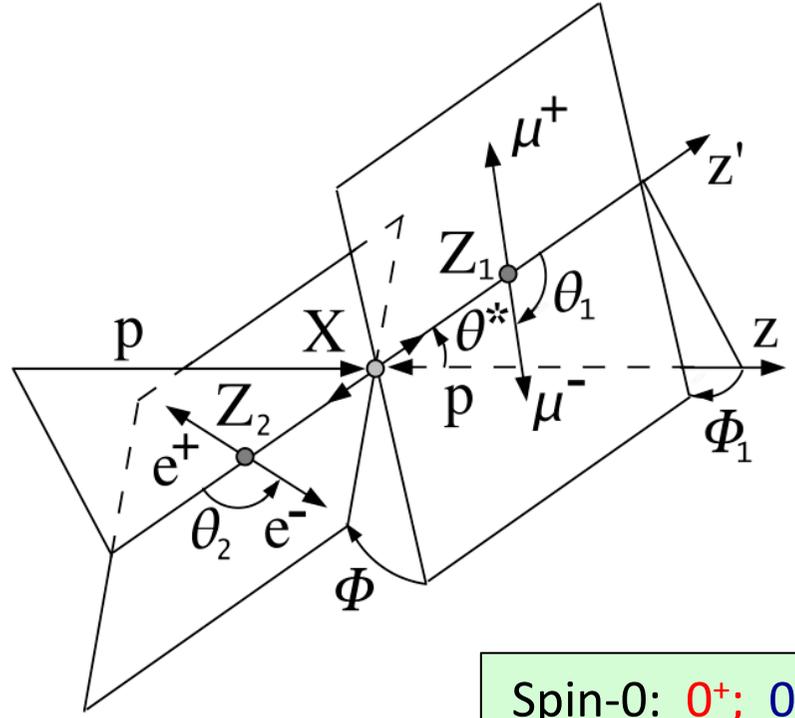
- Left: observed distribution of $|\cos \theta^*|$ in the signal region overlaid with the signal and background components of the pdf obtained from the inclusive fit of the data.
- Right: background-subtracted data distributions, profiled with a fit where the $0^+/2^+_m$ ratio is free.





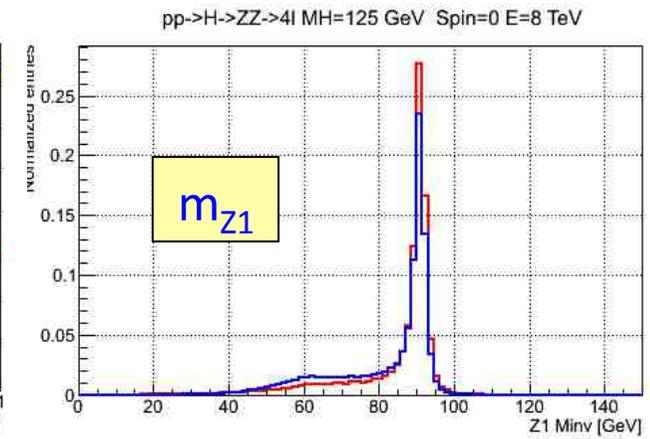
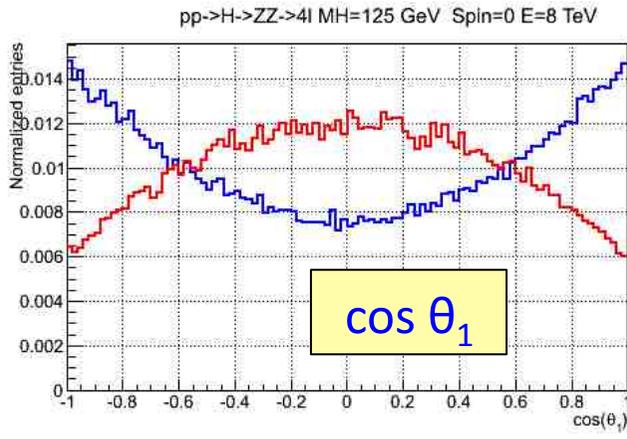
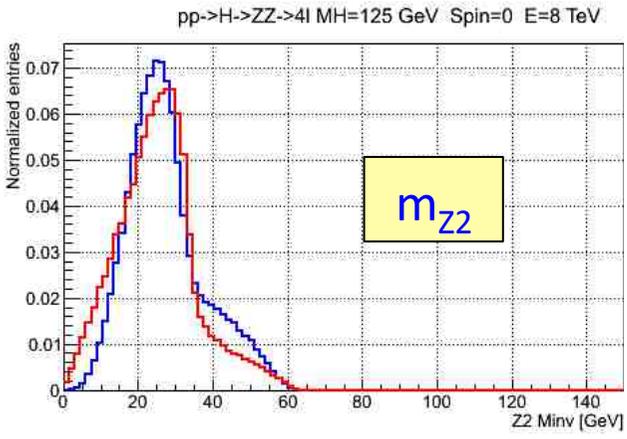
Spin/Parity measurement in $H \rightarrow ZZ \rightarrow 4l$

Sensitivity to all Spin-parity combinations.
5 production and decay angles and reconstructed masses of the intermediate Z's: m_{12} and m_{34} .



Θ^* of the first Z-boson.
 Φ and Φ_1 between the decay planes defined in the Higgs rest frame.
 Θ_1 and Θ_2 of the negative leptons defined in the corresponding Z rest frame.

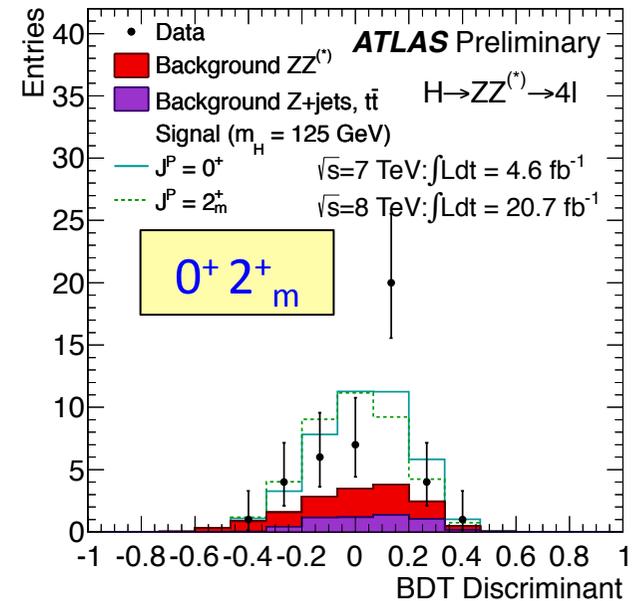
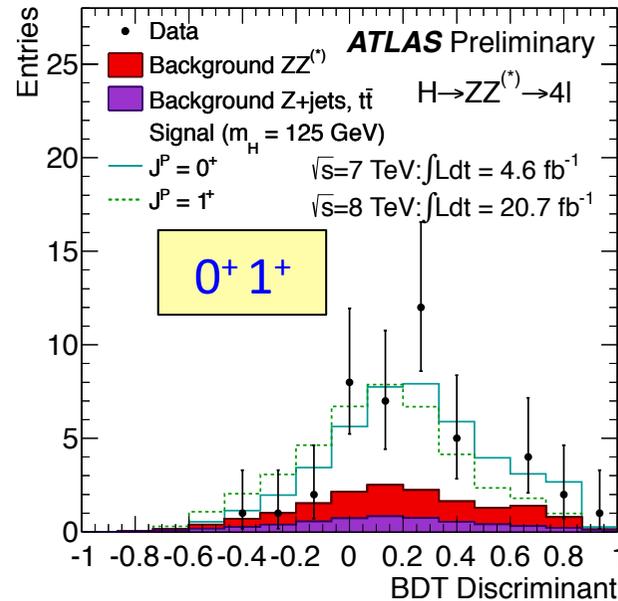
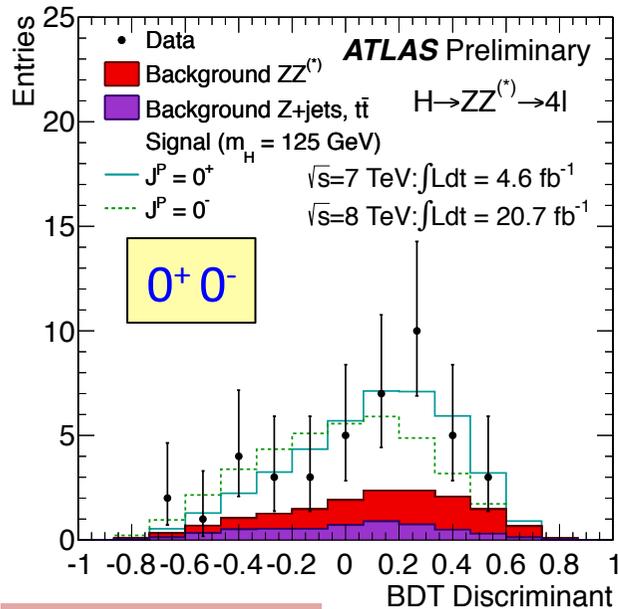
Spin-0: 0^+ ; 0^-





Four lepton decay channel (ATLAS)

- Two complimentary multivariate approaches.
 - BDT analysis: discriminants trained to separate pairs of different Spin/CP states. Training on signal Monte Carlo after full reconstruction and selection.
 - J^P -MELA: discriminants based on the full Matrix Element analytical calculation for each Spin/CP hypothesis.
- Background: from full simulation (ZZ) and from control regions (others).





CMS results



Spin-parity: results

	Expected [σ]		Observed (μ from data)		
	$\mu=1$	μ from data	P(q > Obs alternative) [σ]	P(q > Obs SM Higgs) [σ]	CLs [%]
gg \rightarrow 0^-	2.8	2.6	3.3	-0.5	0.16
gg \rightarrow 0_{h^+}	1.8	1.7	1.7	+0.0	8.1
qq \rightarrow 1^+	2.6	2.3	> 4.0	-1.7	< 0.1
qq \rightarrow 1^-	3.1	2.8	> 4.0	-1.4	< 0.1
gg \rightarrow 2_{m^+}	1.9	1.8	2.7	-0.8	1.5
qq \rightarrow 2_{m^+}	1.9	1.7	4.0	-1.8	< 0.1

Assuming spin-0, fitting for CP-odd contribution gives

$$f_{a3} = 0.00^{+0.23}_{-0.00} \text{ (more in backup)}$$

The studied pseudo-scalar, spin-1 and spin-2 models are excluded at 95% CL or higher



WW spin measurement for Moriond

- The spin analysis leverages the WW rate measurement
 - Same object selections, background samples, many shared systematic uncertainties.
 - Analysis uses the 0-jet e/μ channel only.
- Candidate events are selected with two opposite-charge, different flavor leptons.
- Topological pre-selections optimized to increase acceptance for a spin-2 particle.

event pre-selection

variable	spin	rate
$E_{T,rel}^{miss}$	$> 20 \text{ GeV}$	$> 25 \text{ GeV}$
$p_T^{\ell\ell}$	$> 20 \text{ GeV}$	$> 30 \text{ GeV}$
$m_{\ell\ell}$	$< 80 \text{ GeV}$	$< 50 \text{ GeV}$
$\Delta\phi_{\ell\ell}$	< 2.8	< 1.8



H \rightarrow WW \rightarrow $\nu_e \mu \nu_\mu$ (ATLAS)

